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Systematic Development Of Methodologies In Planning Urban Water Resources For Medium Size Communities, Phase II Final Report

J. W. Delleur
Purdue University, delleur@purdue.edu

J. M. Bell
Purdue University

W. N. Melhorn
Purdue University

L. L. Miller
Purdue University

H. R. Potter
Purdue University

See next page for additional authors

Authors
J. W. Delleur, J. M. Bell, W. N. Melhorn, L. L. Miller, H. R. Potter, and A. R. Rao

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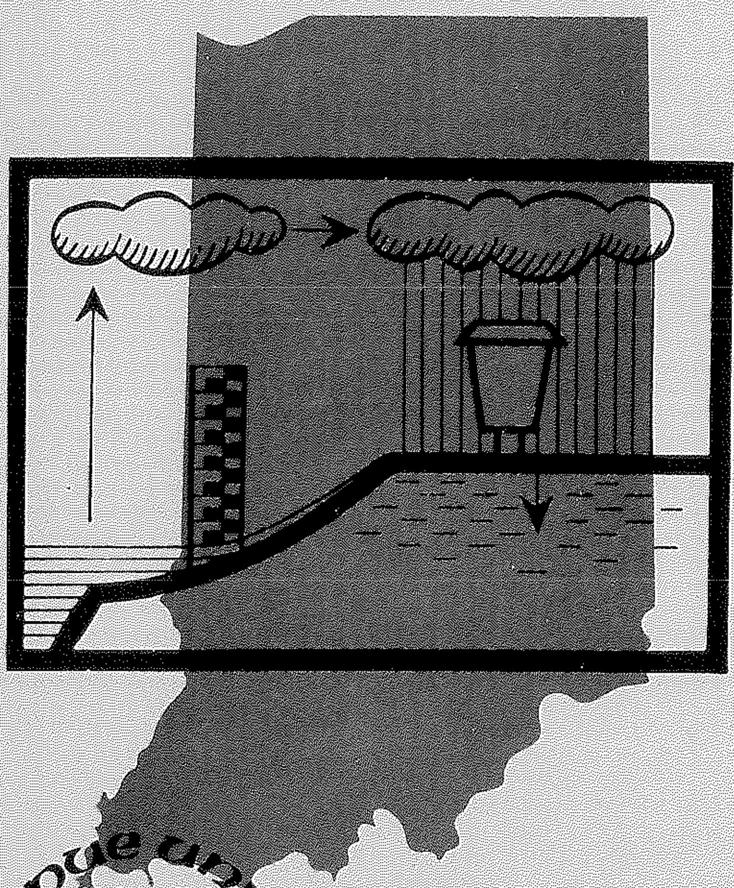
Systematic Development of Methodologies in Planning Urban Water Resources for Medium Size Communities

PHASE II
FINAL REPORT



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J. W. Delleur

J. M. Bell

W. N. Melhorn

W. L. Miller

H. R. Potter

A. R. Rao

August 1979

PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
WEST LAFAYETTE, INDIANA

Water Resources Research Center
Purdue University
West Lafayette, Indiana 47907

SYSTEMATIC DEVELOPMENT OF METHODOLOGIES IN PLANNING URBAN WATER RESOURCES FOR MEDIUM SIZE COMMUNITIES

Phase II
Final Report

by

J. W. Delleur, J. M. Bell, W. N. Melhorn
W. L. Miller, H. R. Potter and A. R. Rao

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ABSTRACT

The principal objective of the research is the development of methodologies in comprehensive planning of water resources of medium size communities (100,000-200,000 inhabitants), and in extending the planning to a 25 to 30 year horizon. The approach is that of systems analysis involving interaction between several research disciplines and with community groups. The disciplines represented in the research are sociology, geology, surface and groundwater hydrology, water quality, economics and land use planning.

The project is divided into two phases. The first phase reported in PWRRC Tech. Rept. No. 74, April 1976, addressed the methodologies of models for estimating population growth, water demand, quantity and quality of surface runoff and availability of groundwater sufficient to supply increasing demand and for determining economic trade-offs between alternate drainage systems.

In the second phase some of the models of Phase I were extended or coordinated. A simpler groundwater model was developed and new causal stochastic models of the groundwater levels were tested. Existing models for the planning and design of urban runoff quantity and quality were extended and improved. Probabilistic and statistical analyses of the urban runoff quantity and quality were performed. These model improvements and these analyses made it possible to design alternate urban drainage systems with several degrees of storage detention and pollution treatment. These several systems were then evaluated for their direct and indirect economic and environmental impacts on the community. Also evaluated was the acceptability of community policies on drainage, land use, urban growth and environmental quality by community leaders and by the general public. The relative aesthetical value of water landscapes in and around urban areas were quantified. In a companion project a multilevel approach was formulated for the systematic planning of urban storm drainage utilities.

As urbanization develops the amount of impervious area in a watershed increases, more precipitation becomes direct runoff and the replenishment of the soil moisture and of the groundwater decreases. The effluent from sewage and industrial plants may become a major portion of low flows in streams flowing through urban areas. Several statistical analyses of the effect of urbanization on low flows and total runoff were performed for six urban streams. The changes in the statistics of the flows and runoffs were observed but the statistical significance of such changes could not be conclusively established because of the small number of available observations.

A new groundwater model was developed by combining the theory of linear systems with the theory of wells. This model is much more economical to use than traditional finite difference models because the expensive pumping tests to determine aquifer transmissivities are not needed. Instead, the model makes use of location and water level histories of existing wells. In addition, stochastic models were developed for the simulation of monthly time series of precipitation, river stages and groundwater levels for the Lafayette region, Indiana.

A substantial portion of the research was concerned with the environmental and economic evaluation of alternate urban drainage systems. For this purpose several simulation models of the urban runoff quantity and quality were utilized. These were the Illinois Urban Drainage Area Simulator, ILLUDAS, developed by the Illinois State Water Survey and the Storage, Treatment, Overflow, Runoff Model, STORM, developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers. A sensitivity analysis of the ILLUDAS model

was performed using data for a 29 acre residential watershed in West Lafayette, Indiana. The program, originally designed for single storm events, was extended so that it can now be used for continuous simulation of the runoff. A water quality subroutine was added for estimating the suspended sediments and BOD in the surface runoff at small time intervals.

The continuous runoff simulation of the program STORM was calibrated and a sensitivity analysis was performed using the same residential watershed. Making use of a 21-year series of hourly rainfall data, simulated series of hourly runoff, BOD and suspended solids were obtained. Extensive statistical analyses were performed and stochastic processes were fitted to the observed and simulated data.

A comparison was made of the results of the simulation program STORM and those obtained by a probabilistic analysis. This study is based on a statistical investigation of the short time increment rainfall process performed in a previous research project supported by OWRT. A storage utilization curve was developed which relates the percentage pollutant overflow to the storage in the watershed for several treatment efficiencies. This curve compared well with the results of STORM once the excessive rainfalls are eliminated and thus provide a useful check on the validity of the output of the program STORM. Rainfalls with the greatest intensity during the first quartile were found to produce the most pollutants. However, these storms are the most receptive to storage retention thus producing the lowest overflow pollution loads.

The program STORM was also used with the same 21-years of record for a 1912 acre urbanizing watershed in the northern portion of West Lafayette. Four treatment rates and four storage capacities were used in several combinations. The program ILLUDAS was then used for the detailed computations of the conveyance system and for the evaluation of alternative storage size and locations.

Two economic models were used to evaluate the direct economic cost of alternative systems and an input-output model was used to estimate the indirect economic impact of the construction of the drainage systems on output, income and employment in the county. Detention storage facilities were found to be needed when the quality of the runoff becomes a critical problem; because the detention storage provides a reduction of the size of the cost intensive treatment plant. Restricting a watershed to 1 or 2 overflows per year is not cost effective, the optimal number of overflows per year appears to be between 4 and 5, resulting in a range of storages between 0.14 and 0.28 watershed-inches.

The acceptability of selected urban water resources policy alternatives to both community leaders and to the general public were evaluated. One-hundred thirty-nine adult residents plus forty-six community leaders of Tippecanoe County, Indiana, were asked their views on drainage, land use, urban growth and environmental quality. About half the respondents indicated some adverse experience with flooding or wet basements, most had no experience with retention basins but expressed concern regarding their safety and proper design. Most were in favor of a firm land use policy to prevent building in wetlands, recognized the importance of local government for decision in water price and quality, and most respondents indicated the desirability of citizens' participation in the decision making regarding natural resources. Water pollution was not seen as a serious problem. Community leaders were willing to pay more taxes than the general public to correct water pollution problems.

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1.1 PROBLEM IDENTIFICATION

Urban planners have developed several land use and city planning models. Most of these have been designed around the transportation systems and have neglected the interaction of land development and urban water resources. In contradistinction, many water models for quantity and/or quality of urban drainage or for water supply and distribution have proceeded somewhat independently of the urban development models.

The larger metropolises such as New York, San Francisco, Detroit, Chicago and Los Angeles have sufficient resources to operate their own planning groups and eventually to develop their own methodologies. However, if one observes the population distribution of the Standard Metropolitan Statistical Areas (SMSA) it is apparent that the mode of the distribution corresponds to medium size communities of the order of 100,000 to 200,000 inhabitants. Communities of this size can, in general, afford only a limited amount of planning effort and do not have the resources to develop their own methodologies. It appears that the need for development of methodologies in comprehensive planning of urban water resources is greatest among these medium size communities. Because of their large number relative to the amount of expertise available, it is not practical or economically feasible to develop new methodologies for each metropolitan area. Although some medium size communities are new cities, such as Columbia, Maryland, and Reston, Virginia, most of the medium size communities are in existence and have varied but generally limited advanced planning. There is a need to extend the planning for these existing communities to a 25 or 30 year horizon.

The concern about the increased runoff due to urbanization developments and the growing concern about the quality of the water in rivers and lakes require that the planning of urban drainage consider the possibilities of detention storages and runoff water treatment facilities. These new facilities increase the complexity and the cost of urban drainage systems. The economic evaluation, the public acceptability, the environmental and aesthetic impacts of alternative urban drainage policies acquire a much larger importance than before.

The problems identified are thus the lack of general methodologies in comprehensive planning of urban water resource facilities for medium size communities and the need of including economic, public acceptability, environmental and aesthetic evaluations of alternative designs as a part of the planning.

1.2 GENERAL OBJECTIVES OF THE RESEARCH

The principal objectives of the research are the development of methodologies in comprehensive planning of urban water resources systems in medium size communities (about 100,000 to 200,000 inhabitants), and in extending the planning to a 25 to 30 year horizon.

The traditional approach to urban water resources systems planning has been that of considering several possible physical systems. In this fashion it is possible to construct a decision theoretic tree in which a large number of options or alternatives are weighted or compared according to some criteria, which often are economic in nature. In contrast the approach used in this research may be called a policy tree. In this approach the inputs are policies such as land use policies, community policies, or other policies which affect the population size and distribution. On this basis a few alternative physical systems may be presented for public decision along with their social, economic, environmental and aesthetic impacts.

The approach used in this research is that of systems analysis involving interactions between several research disciplines and with community groups. The interdisciplinary team represents the different interests involved in the planning of the components of urban drainage systems and in the evaluation of the policies which affect the community. In addition to the obvious technical competence requirement in hydrology, hydraulics, and environmental engineering, economic, sociologic and geomorphologic competence is necessary to analyze the economic impacts of alternate designs, and to evaluate the acceptability and aesthetic merits of urban storm drainage alternatives. The minimum research group should thus include at least experts in the areas of hydrology, hydraulics, environmental engineering, economics, sociology and geomorphology.

This team of researchers worked in close relationship with community groups. It is assumed that a community of the size considered will have some land planning organization; this could be under the form of a city development commission, a county-wide area planning commission, a council of governments or some combination thereof. This group can usually provide a substantial input regarding current land uses and alternative future land uses.

Because of the size of the task the problem was approached in two consecutive phases.

In the first phase of the research (1971-1975) models were developed for: 1) the estimation of the future population, 2) the estimation of the runoff quantity from urbanized areas, (3) the groundwater aquifer geohydrology, 4) the response of an aquifer to different pumping stresses, 5) the economic-environmental evaluation of the trade-offs between alternate urban drainage systems. Procedures were developed for obtaining water quality of storm water runoff from watersheds of varying degrees of urbanization. Rainfall, runoff and storm water runoff quality were monitored at the Upper Ross-Ade Watershed in West Lafayette.

The original objective of phase 2 (1976-1978) was the extension and integration of the models initiated in phase 1 towards an integrated framework for the overall planning of water supply and urban drainage. Due to funding limitations the objectives were reduced primarily to the investigation of urban drainage. A small number of alternative drainage systems were considered and evaluated in terms of their engineering and economic feasibility as well as their environmental and aesthetic desirability. Inputs in the formulation of alternatives are policies, such as land use policies, community policies which affect the population size and distribution.

The models are general in nature, and the methodologies are "transferable," that is, they are not specific to a particular location. This class of models would then be generally applicable to a large number of medium size communities in a broad geographical area.

For the purpose of testing some of the methodologies, data from the cities of Lafayette and West Lafayette in Tippecanoe County, Indiana, were used. It should be stressed that it is not the objective of this research to develop specific plans for Lafayette or West Lafayette. Data from other communities, when more convenient or when appropriate information was not available in Lafayette-West Lafayette, were used. Data from Champaign, Illinois; New York, New York; Indianapolis, Indiana; Iowa City, Iowa; Chicago, Illinois; and Austin, Texas; were used in the study of the effects of urbanization on low flow and total runoff.

In the second phase some of the models of phase 1 were extended or coordinated. A simpler groundwater model was developed and new causal stochastic models of the groundwater levels were tested. Existing models for the planning and design of urban runoff quantity and quality were extended and improved. Probabilistic and statistical analyses of the urban runoff quantity and quality were performed. These model improvements and these analyses made it possible to design alternate urban drainage systems with several degrees of storage detention and pollution treatment. These several systems were then evaluated for their direct and indirect economic and environmental impacts on the community. Also evaluated was the acceptability of community policies on drainage, land use, urban growth and environmental quality by community leaders and by the general public. The relative aesthetical values of water landscapes in and around urban areas were quantified. In a companion project a multilevel approach was formulated for the systematic planning of urban storm drainage utilities.

1.3 STUDY MANAGEMENT

A) The Research Team

The research team consisted of a project director and six principal investigators. The role of the projector director was to serve as a coordinator, to provide the linkages between the several principal investigators, and to provide some guidance and uniformity of purpose for the research. Each principal investigator was assisted by one or more Graduate Research Assistants and Technicians. Each Research Assistant was an advanced degree candidate in one of the disciplines represented in the project.

The research team was structured as shown in Table 1.1. The group met regularly at intervals of about 3 weeks. Dr. Dan Wiersma, director of the Purdue Water Resources Research Center also attended the meetings and he served as project director while J. W. Delleur was on sabbatical leave. J. W. Delleur also served as principal investigator in Hydrology while Dr. A. R. Rao was on sabbatical leave. Except for those meetings concerned with budgetary and administrative matters, the graduate students were in attendance. Several of the research assistants held additional meetings among themselves. The "esprit de corps" developed during Phase I continued and there was a strong spirit of cooperation among all the participants.

B) Interaction with Community Groups and Agencies

The interaction with community citizenry was obtained by directly interviewing a sample of the local population including some community leaders. The results of these interviews are discussed in Chapter 10. Members of the Tippecanoe County Area Planning Commission were invited to make a detailed presentation of future development plans. A post project conference is planned for 1979 to which representatives of federal, state and local agencies will be invited.

1.4 PUBLICATIONS

The publications prepared as part of this research fall under three categories: (a) technical reports, (b) graduate student theses, and (c) journal and conference publications.

A) Reports

PWRRC Tech. Rept. No. 91, "Application of Linear Systems Analysis to Groundwater Evaluation Studies," by C. T. Bathala, A. R. Rao and J. A. Spooner. (This work was initiated under Phase I of this research but not reported in Phase I completion report).

PWRRC Tech. Rept. No. 94, "The Effects of Urbanization on Low Flows and Total Runoff," by R. W. Shanks and A. R. Rao, May 1977.

PWRRC Tech. Rept. No. 103, "Calibration and Sensitivity Analysis of the Continuous Runoff Simulation Model "STORM"," by J. L. Sautier and J. W. Delleur, May 1978.

PWRRC Tech. Rept. No. 105, "Simulation versus Probabilistic Approach for Evaluating Storm Water Treatment Alternatives," by W. Melville and J. M. Bell, June 1979.

PWRRC Tech. Rept. No. 106, "Urban Water Resources Policy Alternatives: A Sociological Analysis of Differential Perspectives," by H. R. Potter, A. Taylor, and G. Grossman.

PWRRC Tech. Rept. No. 108, "A Statistical Analysis of Synthetically Generated Urban Storm Drainage Quantity and Quality Data," by G. Padmanabhan and J. W. Delleur, July 1978.

PWRRC Tech. Rept. No. 109, "Development of an Extension of the ILLUDAS Model for Continuous Simulation of Urban Runoff Quantity and Discrete Simulation of Quality," by J. Han and J. W. Delleur, July 1979.

PWRRC Tech. Rept. No. 110, "Systematic Methodology to Evaluate Scenic Factors of Landscape: Application to Tippecanoe County, Indiana," by M. C. Gardner and W. N. Melhorn, March 1979.

PWRRC Tech. Rept. No. 111, "Economic Impact of Alternative Storm Drainage Systems," by W. L. Miller.

PWRRC Tech. Rept. No. 112, "Systematic Development of Methodologies in Planning Urban Water Resources - Phase II," by J. W. Delleur, J. M. Bell, W. N. Melhorn, W. L. Miller, H. R. Potter and A. R. Rao,

B) Theses

C. T. Bathala, "The Application of Linear Systems Analysis to Groundwater Evaluation Studies," Ph.D. thesis, August 1976, Dr. A. R. Rao, Major Professor (This thesis was initiated as part of Phase I of this research, but was not included in Phase I final report).

Table 1.1 Research Team

Areas	Principal Investigators		Research Assistants (R.A.) & Technicians (T.)		
Project Director	Dr. J. W. Delleur	9/75 - 8/76			
	Dr. Dan Wiersma	9/76 - 8/77			
	Dr. J. W. Delleur	9/77 - 8/78			
Physical Systems	Dr. A. R. Rao	9/75 - 6/77	(R.A.)	A. Prakash	1/76 - 6/76
Hydrology &	Dr. J. W. Delleur	9/77 - 8/78	(R.A.)	J. Han	1/77 - 7/78
Hydraulics	Dr. J. A. Spooner	9/75 - 6/76	(R.A.)	G. Padmanabhan	5/77 - 6/78
Water Quality	Dr. J. M. Bell	9/75 - 8/78	(R.A.)	W. Melville	1/77 - 8/78
Evaluation					
Economic	Dr. W. L. Miller	9/75 - 8/78	(T.)	J. Thompson	6/77 - 8/77
			(T.)	J. Apland	6/77 - 8/77
			(T.)	A. Taylor	6/77 - 8/77
Public Policy	Dr. H. R. Potter	9/75 - 8/78	(R.A.)	G. Grossman	9/76 - 8/78
			(R.A.)	A. Taylor	6/77 - 8/78
Aesthetics	Dr. W. N. Melhorn	9/75 - 8/76	(R.A.)	M. Gardner	1/77 - 8/78

Gary Grossman, "Participation in Community Environmental Decision Making: Leader and Non-Leader Comparisons," Ph.D. thesis, Dec. 1978, Dr. H. R. Potter, Major Professor.

W. Melville, "An Evaluation of the Watershed Model STORM for Management of Storm Water Runoff," M.S.C.E. thesis, August 1979, Dr. J. M. Bell, Major Professor.

R. W. Shanks, "The Effects of Urbanization on Low Flows and Total Runoff," M.S.C.E. thesis, June 1977, Dr. A. R. Rao, Major Professor.

Anne Taylor, "Three Perspectives on Community Problem Solving and Citizen Participation: A Sociological Analysis," Ph.D. thesis, Dr. H. R. Potter, Major Professor.

C) Journal and Conference Papers

C. T. Bathala, A. R. Rao and J. A. Spooner, "Linear System Models for Regional Aquifer Evaluation Studies," Proceedings, Applied Numerical Modelling, Conference held at the Univ. of Southampton, July 1977, pp. 193-204, Pentech Press, London.

C. T. Bathala, A. R. Rao and J. A. Spooner, "Stochastic Models for Groundwater Relationships," Hydraulics in the Coastal Zone, Proceedings, 25th Annual Hydraulics Division Specialty Conference, Texas A&M Univ., August 1977, pp. 211, abstract only, ASCE 1977.

A. R. Rao and R. G. S. Rao, "Analysis of the Effects of Urbanization on Runoff by Nonlinear Functional Series Model of Rainfall-Runoff Process," Proceedings, Intl. Symp. on Urban Hydrology, Hydraulics and Sediment Control, Univ. of Kentucky, July 1977, pp. 209-220.

R. W. Shanks and A. R. Rao, "The Effects of Urbanization on Low Flows and Total Runoff," Hydraulics in the Coastal Zone, Proceedings of the 25th Annual Hydraulics Division Specialty Conference, Texas A&M Univ., August 1977, pp. 203-210, Am. Soc. Civil Engrs., 1977.

J. L. Sautier and J. W. Delleur, "Calibration and Sensitivity Analysis of the Continuous Runoff Simulation Model "STORM"," Proceedings Intl. Symp. on Urban Storm Water Management, Univ. of Kentucky, July 1978, pp. 73-79.

G. Grossman and H. R. Potter, "A Trend Analysis of Competing Models of Environmental Attitudes," Working Paper No. 127, Institute for the Study of Social Change, Department of Sociology and Anthropology, Purdue University, 1977.

G. Grossman and H. R. Potter, "A Longitudinal Analysis of Environmental Concern: Evidence from National Surveys," Working Paper No. 142, Institute for the Study of Social Change, Department of Sociology and Anthropology, Purdue University, 1977.

H. R. Potter, "Citizen Participation in Natural Resources Decision Making: Conceptual Issues and Approaches," Working Paper No. 157, Institute for the Study of Social Change, Department of Sociology and Anthropology, Purdue University, 1978.

J. W. Delleur, W. L. Miller and H. R. Potter, "Interaction Between Land Use and Urban Water Resources Planning," Water Resources Bulletin, Vol. 12, No. 4, P. 759-777, Aug. 1976.

J. W. Delleur, J. M. Bell, W. N. Melhorn, W. L. Miller, H. R. Potter and A. R. Rao, "Effectiveness of Urban Drainage Models for Planning and Design in Medium Size Communities," in Tech. Memo No. 36, Amer. Soc. Civil Engrs. Urban Water Resources Research Program, June 1976.

J. W. Delleur, J. M. Bell, W. N. Melhorn, W. L. Miller, H. R. Potter, and A. R. Rao, "Methodologies in Planning Urban Drainage Systems for Medium Size Communities," Proceedings, Intl. Symp. on Urban Storm Runoff, Univ. of Kentucky, July 23-26, 1979, p. 349-358.

D) Related Publications in Project OWRT-B-083-IND

PWRRC Tech. Rept. 100, "Urban Growth in Water Resources Planning," by S. A. Dendrou, J. W. Delleur and J. J. Talavage, April 1978.

PWRRC, Tech. Rept. 101, "Urban Storm-Drainage System Planning," by S. A. Dendrou, J. J. Talavage and J. W. Delleur.

S. A. Dendrou, J. W. Delleur and J. J. Talavage, "Systematic Planning of Urban Storm-Drainage Utilities," Proceedings Intl. Symp. on Urban Storm Water Management, Univ. of Kentucky, July 1978, p. 229-234.

S. A. Dendrou, and J. W. Delleur, "Reliability Concepts in Planning Storm-Drainage Systems," Proceedings Intl. Symp. on Risk and Reliability in Water Resources, Univ. of Waterloo, Ontario, Canada, June 1978, Vol. 1, pp. 390-410.

S. A. Dendrou, J. W. Delleur and J. J. Talavage, "Planning Storm-Drainage Systems for Urban Growth," Jour. of the Water Resources Planning and Management Division, Amer. Soc. Civil Engrs., Nov. 1978.

S. A. Dendrou, J. J. Talavage and J. W. Delleur, "Optimal Planning for Urban Storm Drainage Systems," Jour. of the Water Resources Planning and Management Division, Amer. Soc. Civil Engrs., Nov. 1978.

E) Related Report in Project A-053-IND

PWRRC Tech. Rept. No. 107, "Participation in Water Resources Planning: Leader and Non-leader Comparisons," by H. R. Potter, G. Grossman, and A. Taylor.

F) Supplementary Report

PWRRC Tech. Rept. No. 118, "A Comparative Application of Several Methods for the Design of Storm Sewers," Sept.1979, by C. B. Burke and D. D. Gray.

1.5 SUMMARY OF THE REPORT AND CONCLUSIONS

A) Groundwater

In Phase I problems were encountered in the formulation of digital models for groundwater evaluation because of the large requirements of data, manpower and computational expenditure. A previously proposed model was adapted for predicting the response of an aquifer under different hydrologic stress. The linear systems approach is combined with the theory of well hydraulics to obtain a model which considers only the cause-and-effect relationships of the groundwater system. The procedure developed was found to be simpler and less expensive than the finite difference-type models. The location of the existing and planned wells constitute the number of nodes in the model. The number of nodes increases only with the number of wells and is independent of the areal extent of the aquifer. Because of the relatively small number of nodes the computation time is much smaller than in conventional finite difference models. Unlike other deterministic models, the predetermined aquifer transmissivity values are not used as input. Only estimates of the storage coefficient are used in the model. These estimates can be obtained from an examination of the geology and of the well logs of the area. Consequently, expensive pumping tests which are usually required to determine the aquifer transmissivities and storage coefficients are not needed in the present procedure. The number of computation trials with the present procedure is smaller than that required in finite difference models and in electric network simulator. The computational expenditure is thus drastically reduced in the present procedure.

A new technique for the development of causal stochastic models has been tested in the Lafayette area for the simulation of time series of precipitation, river stages and groundwater levels. For a well in an unconfined aquifer the model for the monthly groundwater levels includes seasonal terms, autoregressive terms and residual terms either from the monthly precipitation model or from the river stage model, indicating a causal relationship between precipitation or river stage and groundwater level. The stochastic model for the monthly groundwater levels for a well in a confined aquifer does not include any residual term from either the precipitation or the river stage models.

B) Effect of Urbanization on Low Flows and Total Runoff

The increase in surface runoff due to urbanization was studied in Phase I. Linear and nonlinear lumped rainfall-runoff models were developed and tested on the Salt Creek basin at Arlington in the Chicago metropolitan area. The portion of Phase II of the project concerned with surface water hydrology focussed on the effects of urbanization on low characteristics and on total water yield of streams flowing through urban areas. In such streams, as the amount of impervious area in the watershed increases, more precipitation becomes direct runoff, the replenishment of the soil moisture and of the groundwater decreases, and the effluent from sewage and industrial treatment plants may become a major portion of the low flow in the stream. Six urban streams located in Indiana, Illinois, Iowa, New York and Texas were studied. Several types of statistical analyses were performed. The date at which the urbanization started to have a measurable effect on the low flows was obtained by means of mass curves for 1 and 7-day low flows and for total runoff. A flow duration analysis of daily flows showed that, for a given probability of exceedance, the daily flows increased in four cases and decreased in 2 cases as a result of urbanization. A linearized rainfall-runoff relationship showed that in the same four cases the quantity of annual runoff increased whereas the other two cases showed decreases. However it was not possible to conclusively establish the statistical significance of the changes observed in the low flows and in the total runoff sequences because of the small number of available observations.

C) Sensitivity Analysis and Extensions of Surface Runoff Simulation Models

A substantial portion of Phase II of the research was concerned with the environmental and economic evaluation of alternate urban drainage systems. For this purpose several simulation models of the urban runoff quantity and quality were utilized. These were the Illinois Urban Drainage Area Simulator, ILLUDAS, developed by the Illinois State Water Survey; and the Storage, Treatment, Overflow, Runoff model, STORM, developed by the Hydrologic Engineering Center, U. S. Army Corps of Engineers. Extensions of the ILLUDAS model were developed as part of this research.

The model ILLUDAS was selected for the simulation of the rainfall-runoff process because of its accuracy and flexibility. A sensitivity analysis of this model was performed using data for the Upper Ross-Ade Watershed, a 29 acre single housing development, in West Lafayette, Indiana. It was found that the proper selection of the soil group and antecedent moisture condition was critical for this type of suburban watershed. A time increment equal to the average inlet time, 5 minutes in this case, was found to be the largest time increment for which accurate hydrographs could be obtained. The computer program ILLUDAS has two basic limitations: 1) the program is designed for single storm events and there is no provision for continuous simulation, 2) there is no runoff quality calculation. Extentions to this program were developed to eliminate these limitations. A subroutine was added which performs a continuous accounting of the antecedent soil moisture. A modification of a subroutine from the program STORM for the estimation of suspended solids and BOD was added to the program ILLUDAS. The pollutographs calculated in this manner for the Upper Ross-Ade watershed were consistently closer to the observed pollutographs than those estimated by the program STORM.

In contradistinction to the program ILLUDAS designed for the hydrograph evaluation from existing storm sewers or for the design of new storm sewers, the program STORM is a model for the planning of urban drainage systems. STORM utilizes a time interval of one hour. A calibration and a sensitivity analysis of the continuous runoff simulation portion of the model STORM were performed using data from the Upper Ross-Ade watershed in West Lafayette, Indiana. The program STORM has two options for the runoff calculations. Option I makes use of the composite runoff coefficient and Option II uses the

Soil Conservation Service method for the pervious areas and the composite runoff coefficient for the impervious areas. It was found that up to 38% imperviousness, and probably up to 30% the results provided by Option I are more accurate than those provided by Option II. In Option I the impervious runoff coefficient is a decisive parameter and its determination requires great accuracy. In Option II the decisive parameter is the maximum soil moisture retention capacity.

D) Statistical and Stochastic Analyses of Simulated Quantity and Quality of Urban Runoff

Making use of the model STORM calibrated for runoff quantity and quality on the Upper Ross-Ade watershed in West Lafayette, Indiana, and using a 21 year time series of recorded hourly rainfalls near the watershed, simulated series of hourly runoff, BOD, and suspended solids were obtained for the same 21 year period (1954-1974), for the assumption of no storage and no treatment. A detailed statistical analysis was performed on these 1826 storm events. Significant regression equations were obtained between rainfall and suspended solids, and rainfall and BOD, the rainfalls being classified according to their durations from 1 to 6 hours in steps of one hour. Extreme value and partial duration analyses were performed for rainfall, runoff, suspended solids and BOD. For estimating the suspended solids and BOD for a given return period it is suggested to use the rainfall frequency curves, based on observed rainfalls, and the regression equation to obtain the corresponding expected suspended solids and BOD. A mixed autoregressive model of order one and a moving average model of order one were fitted to the cyclicly standardized series of monthly rainfall, runoff, suspended solids and BOD. These models can be used to generate synthetic series for each of these four variables which have the same statistical properties as the historical series for the rainfall and as the STORM generated series for the other variables.

The program STORM was also used with the same 21 years of record for a 1,912 acre watershed located in the northern portion of West Lafayette, Indiana. Four treatment rates and four storage capacities were used in several combinations. The program ILLUDAS was then used for the detailed computations of the conveyance system and for the evaluation of alternative storage sizes and locations. This information was then used as an input in the economic evaluation of alternate drainage systems.

E) Probabilistic Evaluation of the Results of the Program STORM

A comparison was made of the results of the simulation program STORM and of those obtained by a probabilistic analysis. The probabilistic analysis is based on a statistical analysis of the short time increment rainfall process developed by Grace and Eagleson at MIT and tested for West Lafayette in a previous OWRT project. Rainfall depths, d, at 10 minute intervals were classified as trace ($d<0.03"$), moderate ($0.03"<d<0.09"$) and peak ($d \geq 0.09"$). Each class was classified in 9 subclasses according to duration for each class. From this previous statistical analysis the cumulative distribution of rainfall depth was obtained. Making use of the results of the program STORM applied to the Upper Ross-Ade watershed in West Lafayette, Indiana, a cumulative distribution of the suspended solids was also prepared. It was then observed that there is an almost linear relationship between the accumulated rainfall and the accumulated suspended solids. This is to be expected, as it has been seen earlier that good regression relationships had been obtained between rainfall classified by duration and suspended solids. Nevertheless for storms larger than about 3" the suspended solids tend to become independent of the rainfall as for larger storms all the available pollutants have already been washed off. Applying this relationship between rainfall and suspended solids to the probability of exceedance of a given storage depth a storage utilization curve is obtained. This curve relates the percentage of pollutant (suspended solids) overflow to the storage in the watershed for several treatment efficiencies. This storage utilization curve may then be compared to the results obtained from the simulation results of the program STORM obtained by applying the series of 22 years of hourly rainfall at the Agronomy Farm to the 1,912 acre watershed in Northern West Lafayette. There is a distance of about 6 miles between the rain station and the watershed. The results compared well for the practical range of design storages, between 0.14 and 0.28 watershed-inches, and once the excessive storms had been eliminated. The excessive storms are those which produce 1.0 treatment plant overflow per year according to the STORM simulation for a specified treatment rate and storage capacity (0.06 in/hr T.R. and 0.28 watershed-inches of storage in this case). These events have large depths and/or very intense rainfall periods. About 1/3 of these excessive storms are more intense than the 5 year storms. These excessive storms cause unusually large erosion. These storms are considerably more severe in their pollution potential, and this pollution load is not practically or economically treatable. The expected storage utilization curve serves as a useful check of the validity of the output of the program STORM.

Storms may also be classified according to the quartile in which the greatest intensity occurs. The effectiveness of storage on the retention of peak storms of various quartiles was evaluated. The first quartile storms produce the most pollutants, and the majority of the pollutants are generated in the first half of the runoff volume. However the first quartile storms are the most receptive to storage retention (the storage is assumed empty at the beginning of the storm) thus producing the lowest overflow pollution loads.

Making use of the economic analysis discussed in the following section and the systems analysis discussed in the last section, it appears that the optimal number of overflows is between four and five. In a watershed with only 1 or 2 overflows of its treatment plant per year, it is not cost effective to build retention storage.

F) Economic Evaluation of Urban Drainage Systems

The economic study attempts to evaluate the policy implications of alternative drainage systems, and to improve the methodology for such an evaluation. Particular attention was directed to the evaluation of both the direct and the indirect impact of alternate designs. Fifteen alternate drainage systems were considered for the 1,912 acre watershed in northern West Lafayette, with detention storages varying between zero and approximately 2 million cubic feet, and treatment plants with rates of 75 MGD, 25 MGD and 12.5 MGD.

Two models were used to evaluate the direct economic cost of alternative systems. A simulation model was developed to test the sensitivity of the cost of the drainage system to variation in the level of operating and maintenance costs. This model calculated the present value of the capital, operating and maintenance cost of each system. The second model is an average annual cost model. It was used to evaluate the combination of the drainage system and treatment plant costs. The indirect economic impact was also evaluated as the construction of an urban drainage system provides additional employment and income in the construction industry. The input-output model of Tippecanoe County was used to estimate the impact of these spendings on output, income and employment in the county.

When urban development occurs the least costly drainage system involves combining some of the open channel drainage systems (lined with concrete if necessary) with storm sewer pipes from the new subdivisions. Detention storage is more costly than storm sewer pipes alone even when the storage is a low grass area in a recreational park. A single storage facility is generally less costly than multiple detention facilities. When a change in the runoff hydrograph is not permitted as the area changes from rural to urban, substantial and costly detention storage may be required. Likewise detention storage facilities are needed when the quality of the runoff becomes a critical problem. The detention storage provides a reduction of the size of the treatment plant which requires high capital cost and high operating cost. The reduction in cost that results from the installation of a smaller treatment plant exceeds the cost of providing detention storage facilities. Of course, the indirect economic impact is directly proportional to the direct cost.

In the case of a need of compromise from the optimal storage-treatment combination, preference should be given to storage. The optimal number of overflows per year on an economic basis corresponds to the optimal number of overflows based on water quality. The number of overflows versus storage obeys the law of diminishing returns.

G) *Evaluation of Acceptability of Alternative Urban Water Policies*

The acceptability of selected urban water resources policy alternatives to both community leaders and to the general public was evaluated. The study concentrated on drainage, land use, urban growth and environmental quality. The specificity of policy alternatives, the number of alternatives, the relative importance of water resources issues, the familiarity and knowledge about water issues and public participation in the policy process were implicit problems considered in this evaluation.

The specificity of the questions was varied. For example, more detailed questions were asked about drainage, somewhat more general questions were posed about land use and urban growth, and the most general questions were asked about pollution or environment.

A sample of two hundred adult residents, one per household, was selected. Of these, 139 were interviewed. In addition, 46 "positional" and "reputational" community leaders were interviewed. The survey covered the northeast half of Tippecanoe County, Indiana, which includes the two cities of Lafayette and West Lafayette, and most of the area directly affected by urbanization. The area immediately adjacent to Purdue University was omitted.

Two criteria were used in the sampling plan: one was geographic location with the categories of urbanized, transitional and rural; the second stratification criterion was social class using mean value of housing by block. This methodology, of course, is not limited to the Lafayette-West Lafayette SMSA but is generally applicable in medium size communities.

The findings include a moderate degree of concern about the environment generally, and water pollution in particular, in the study area. The concern among rural residents and leaders was particularly high. Four specific problems were included: flooding or wet basements, sewer pipes backing up, low water pressure, and water being cut off for repairs.

About half the respondents had experienced flooding or wet basements, and about 40% indicated the presence of poor drainage in their areas, of these 22% indicated it was a major problem in their neighborhood and 55% said it was a minor problem. Ninety percent of the respondents had never lived near retention basins, but over 60% expressed some concern about them. Mosquitos, other health and safety reasons and problems associated with proper design, construction and maintenance were the main reasons for concern.

Regarding the method of drainage, open ditches or retention basins, rural residents were the least concerned and transition area residents were the most concerned probably because they live in the area undergoing most rapid land use change.

Concerning the responsibility of land use in relation to drainage, the developer and the state government were each named by about 60% of the respondents, but 89% of the leaders thought local government should be responsible. The majority favored a firm policy to prevent people from building in wet lands and in areas which are low or poorly drained.

A large number of respondents think first of local government for decisions on water prices and quality. This suggests the importance of local government in people's mind despite the substantial role of state and federal government in water resources.

Water pollution was not seen as a serious problem by most respondents. In general, leaders saw water pollution as less serious and getting better more often than the general public. They were also willing to pay more in taxes, and in larger amounts than the general public. The majority of respondents were concerned about the loss of farmland to urban uses, although leaders were somewhat less concerned than the general public. In contrast the respondents were fairly evenly split regarding the desirability of annexation by the city of surrounding developments, and regarding urban growth.

The great majority of the respondents, 76%, thought citizens should participate in the decision making process regarding natural resources; the percentage was higher among rural residents (90%) and leaders (85%) and 14% of the respondents indicated they were currently involved. There is a substantial belief in public involvement independent of political views.

H) Aesthetic Evaluation of Water-Related Scenes in Urban Developments

The aesthetic evaluation was oriented towards the identification of areas of unusual beauty, particularly water-related scenes, that may need protection from future growth of urban areas. A methodology was developed to identify areas of unusual scenic quality. Previous studies of the riverine environment have concluded that scenic quality in a landscape increases as the abundance and diversity of surface water increases. Surface water characteristics that are most pertinent to these scenic standards are: drainage density, drainage frequency, drainage order, drainage pattern, drainage texture, number and size of lakes and number and size of swamps. In general, it can be assumed that agricultural and forest land uses are neutral or positive aesthetic elements of the cultural environment. Industrial, commercial and residential land use practices are normally antithetical to scenic beauty.

On the basis of surface morphology and cultural use of the land fifty landscape units were delineated in Tippecanoe County. Areas of similar relief, landform characterization, elevation, and land use constitute discrete landscapes. "Evaluation categories" were assigned to all "descriptive factors" in each landscape including the pertinent physical, biological and cultural elements. These descriptive factors and criteria must be adjusted for different physiographic regions. A total of 336 field stations were utilized for field observations.

The "uniqueness ratio" defined by Leopold, and the "uniqueness index" defined by Melhorn were used to quantify the evaluation of scenic riverscapes and landscapes. Based on the uniqueness index and uniqueness ratio an aesthetic index was developed which is a measure of what constitutes beauty and ugliness in a landscape. These several indices are relative measures and serve only to hierarchically rank the landscapes of each section in order of aesthetic quality according to the evaluation criteria.

Nine landscapes were determined to be most scenic in Tippecanoe County; of these five were stream valleys. The Middle Wabash Valley ranked very high in uniqueness but was given the lowest aesthetic index due to urbanization. Lakes are very rare in this area. In developing communities, such as Lafayette, and West Lafayette, the presence of scenic lakes increases property values greatly. For these reasons, it is very important to preserve the few natural lakes which exist in Tippecanoe County.

The effects that poor management and planning can have on small lakes undergoing urbanization were examined. An example was given of how a lake built to enhance property values through aesthetic appeal became an eyesore which detracted greatly from the surrounding area.

Locally, 83% of the respondents to the questionnaire previously described believed that land should be zoned for the protection of scenery. With the tools of quantitative aesthetic evaluation it becomes the responsibility of the planners and policy makers to decide the fate of these scenic resources.

I) Systematic Planning Methodology

In a parallel project (B-083-IND) a systematic methodology for the planning of urban storm-drainage utilities was developed. A computer program package was developed that integrates and interfaces an urban growth model, LANDUSE, and an urban hydrology model, a modified version of STORM. Alternate growth scenarios can thus be directly related to the corresponding storm-drainage systems. If these systems are designed to achieve specified standards of performance, then a useful comparison among several possible urban growth patterns can be performed. While an urban area encompasses several natural watersheds, the hydrologic models simulate one watershed at a time. The different watersheds that partition an urban agglomeration create a tree-like or dendriform configuration. The planning of a global storm-drainage system for such a configuration of basins can be effectively accomplished by a coordination of the interactions among the different basins. This resulted in a multi-level coordination problem among the basins of the watershed. The storm-drainage planning model was defined at the watershed level, and the optimization was achieved by a multilevel feasible decomposition scheme, where the landuse based hydrologic siumlation model (LANDUSE + STORM) was used locally and separately for every local basin. A constrained cost-optimization scheme was adopted for the solution procedure. The resulting coordinating algorithm was proven to converge to the minimum cost solution under some minor conditions of regularity of the modeling equations.

This methodology can be used for changes to existing storm-drainage systems, or in planning to accomodate urban growth simulated by the LANDUSE model. For several such projections associated with a given watershed the model can associate unique storm-drainage system cost with each land use projection. The methodology was tested on the case of a 25 year land use projection for West Lafayette, Indiana.

J) Conclusion and Application of the Results

The newly developed groundwater model is of immediate application in situations where the expense of a finite difference model or of an electric analog model is not warranted, as in medium size communities which derive their water supply from groundwater. The new model provides the engineer with a simpler and less expensive tool for the evaluation of the aquifer response to anticipated stresses due to increasing water demand.

With the modifications introduced into the ILLUDAS program, it is now possible to obtain a continuous short time interval simulation of the urban runoff quantity, suspended solids and BOD loads. This information is becoming necessary for the evaluation of storage detention and pollution load for the control of non-point source pollution from urban areas.

The methodology for the development of a storage utilization curve based on short-time rainfall statistics makes it feasible to obtain preliminary estimates of pollutant overflow in terms of the runoff storage in the watershed and runoff treatment efficiencies without utilizing elaborate computer programs such as STORM. Alternatively, the methodology can be used to check the results of the program STORM. The several regression expressions make it possible to obtain a preliminary estimate of urban runoff pollution load from similar residential areas without the need of complex simulations.

The methodology developed for the economic evaluation of alternative drainage systems clearly indicates that detention storage is not cost effective if its sole purpose is to reduce the size and cost of storm sewer pipes. On the other hand, detention storage facilities are needed when the quality of the runoff becomes a critical problem. The determination of the appropriate sizes of storage facilities and of the runoff treatment rate become crucial in the design of cost effective drainage systems. The case study for a watershed in northern West Lafayette is based on 1977 costs and provides an example for the economic evaluation of new storm drainage systems with and without pollution control facilities.

The evaluation of urban water resources policies to community leaders and to the general public provides some guidelines which are certainly valid in Indiana and in the Midwest and probably in a much wider geographical area and should be useful in the development of new urban areas. The general public has a feeling of caution regarding the use of detention storage, favors strong land use policies to prevent building in wetlands and for the protection of scenery, looks first at the municipal government for the solution of water problems, but are less willing than community leaders to pay more taxes for the correction of water pollution problems.

The methodology developed in the companion project OWRT-B-083-IND can be used to plan for changes to existing storm drainage systems or in planning to projected urban growth.

Chapter 2
Specific Objectives of the Research

The investigation is divided into two main parts: physical systems and objective evaluation. The specific objectives for each part are listed below.

2.1 PHYSICAL SYSTEMS

1. To continue the development of storm runoff water sampling methodology for the economical procurement of representative samples for subsequent analysis.

2. To develop deterministic models, with or without stochastic inputs, from field data involving such parameters as water quality, type of watershed, rainfall duration, rainfall intensity and antecedent dry period.

3. To generate and evaluate several alternative solutions with respect to detention, collection, transportation, treatment, recharge, disposal and/or reuse of storm water runoff in the framework of optimum utilization of this important segment of the management of the total water resources of a community.

4. To investigate the effects of urbanization on low flow characteristics of urban streams.

5. To investigate the effects of urbanization on total runoff and on water yield from streams in urban areas.

2.1 EVALUATION

1. To measure and compare the direct economic impact of alternative drainage systems.

2. To develop improved methodology to measure the indirect economic impact associated with the development of alternative systems designed in (1) above.

3. To determine the position of public policy decision makers with regard to acceptability of such alternative futures and systems.

4. To determine the position of the general public as to the acceptability of such alternatives.

5. To develop an urban environmental-aesthetic index or matrix with emphasis on water-oriented aspects of natural and programmed environments.

6. To evaluate the role of population distribution and community policy decisions as related to burdens placed on the local ecological system and the resultant impacts on environmental quality.

2.3 GENERAL

To establish the means for appropriate communication and implementation of the basic methodologies of water resources management developed through the project.

CHAPTER 3
GROUNDWATER HYDROLOGY

3.1 INTRODUCTION

The demand for water is rapidly increasing due to growth in population and urbanization. In many regions, groundwater is an important source to meet this increased demand and hence proper regional planning and utilization of groundwater resources demand our attention. During the past few years, considerable effort has been directed toward the analysis of these groundwater resources. In view of the large expenditure involved in these aquifer evaluation studies, better aquifer modeling techniques are of vital importance.

In Phase I Bathala, Spooner and Rao (1976) have investigated the problems encountered in formulating digital models, especially those related to the data, manpower and computational expenditure. They concluded that the results from digital models developed by using limited available data should be interpreted with caution. Several other investigators have also emphasized the restrictions imposed by the lack of data and budgetary constraints. The main objective of this study was to explore the feasibility of constructing a digital model for aquifers underlying medium size communities and to explore difficulties that may arise due to limitations on the data, computational expenditure and availability of skilled manpower. The glacial aquifer underlying Lafayette and West Lafayette, Indiana, covering an area of about 26 sq. miles, was selected as a test site. A digital computer model was formulated by using a rectangular finite difference grid system consisting of 24 columns and 33 rows with 792 nodes. Only the historical record of water levels, pumping rates and pumping test data were used in developing this model. These data were not sufficient either to prepare reasonably accurate piezometric surface maps or to estimate the aquifer properties satisfactorily. However, considerable effort and expenditure was involved in the development of this model.

The approximate overall computer related expenditures corresponding to different stages during the development of this model is presented in Table 3.1. It was concluded from the above study that the data requirements and budgetary constraints play a major role in the formulation and operation of digital groundwater models. The study also suggested the need for developing less expensive methodologies for estimating aquifer capacities.

In view of these considerations, there is a need for developing less expensive methodologies for the evaluation of groundwater resources. It would be highly desirable if these methodologies could use essentially the historical record of groundwater levels, pumping rates, precipitation and streamflow. Therefore, the development of such simpler methodologies was the main objective of the study which was completed under Phase II.

The linear systems approach which has been gaining favor for the past few years appears to be an efficient tool for developing less expensive and comprehensive models for regional groundwater resource evaluation. However, there is a common drawback with most of these deterministic models presently used. As far as the authors are aware, these models (except those on stream-aquifer interactions) use predetermined aquifer transmissivity and storage coefficient values as the primary input variables. It is difficult to obtain these values where suitable pumping test data are lacking. It is, therefore, highly desirable to couple the theory of well hydraulics with the linear systems approach to develop a model which considers only the cause-and-effect relationships of the groundwater system.

Another aspect that is of interest in the development of aquifer flow models is the stochastic nature of groundwater levels. Rainfall is the major source of recharge to the groundwater basin in many situations. The amount of this recharge is

Table 3.1 Computational Cost of Modeling

S.No.	Item	Approx. Cost
1	Data processing and preliminary computer runs	$ 2,000
2	Calibration of the Digital Model	$ 4,500
3	Development of Stochastic Models	$ 800
4	Estimation of Aquifer Capacity (Final Runs)	$ 2,900
5	Miscellaneous	$ 500
	Total	$10,700

dependent on the infiltration characteristics of the soil. The depths of ground water levels also affect recharge in terms of time of travel and intermediate losses. Where circumstances are favorable, surface streamflow also interacts with the groundwater system. When groundwater levels are near the surface, the effects of evaporation and transpiration may be significant. Pumpage from wells constitute the major artificial discharge of ground water. The groundwater levels will go down when the pumping rates are higher than the recharge rates. In essence, groundwater levels in an aquifer system are affected by several stochastic processes such as precipitation, infiltration, evapotranspiration, streamflow and pumpage. Consequently, groundwater levels also constitute a stochastic process.

3.2 OBJECTIVES OF THE PRESENT STUDY

Based on the foregoing discussion the objectives of the present study are as follows:

1) To develop a procedure for predicting the response of an aquifer system under different hydrologic stresses by considering only the cause-and-effect relationships of the system.

2) To apply the above procedure for predicting the response of the groundwater system in field situations.

3) To investigate the utility of the above procedure to replace the traditional type curve solution for pumping test analysis.

4) To investigate the causal relationship of different hydrologic variables affecting groundwater levels.

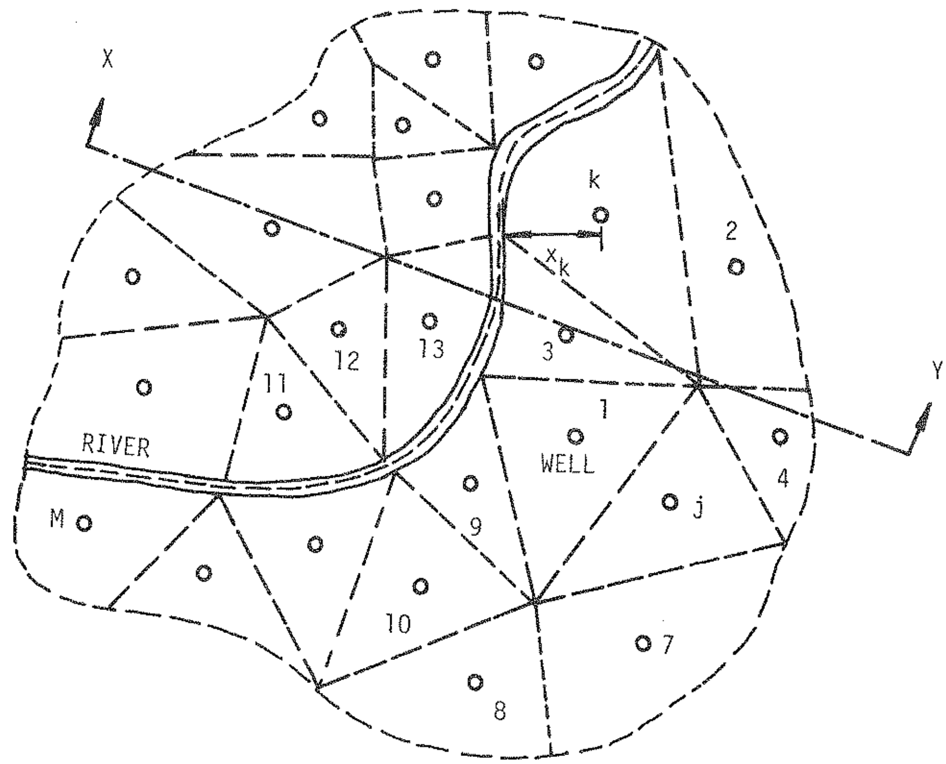
3.3 METHODOLOGY - LINEAR SYSTEM MODELS - DETERMINISTIC APPROACH

Any stationary system satisfying the laws of superposition and proportionality can be considered to be a linear system. Several types of groundwater flow systems can be considered stationary, and they also satisfy the laws of superposition and proportionality. Consequently, most of the groundwater problems can be solved using linear systems theory. Another important advantage of the linear approach is that known solutions of heat conduction problems can be used by analogy for solving quite a few groundwater flow problems.

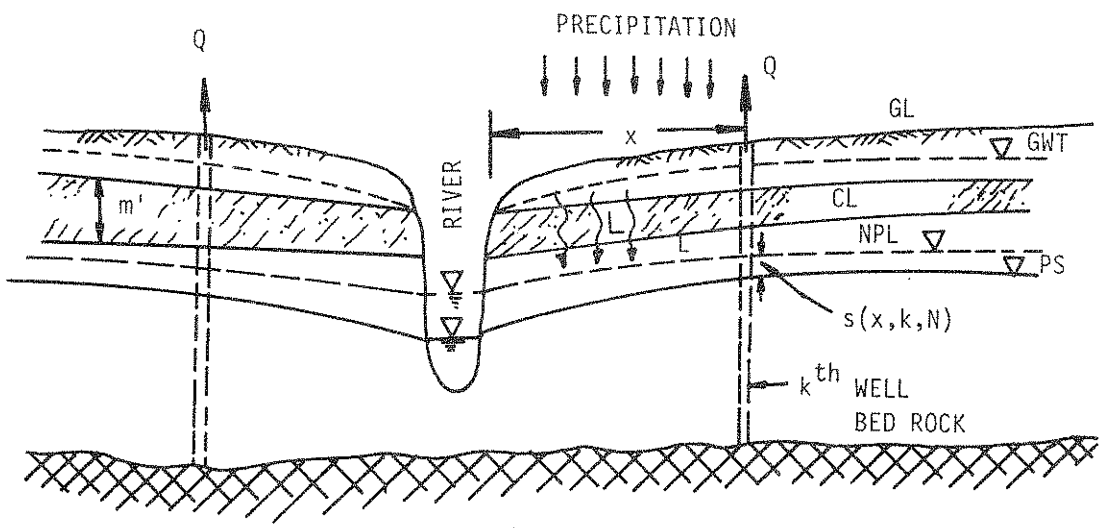
A) *Theoretical Formulation*

Consider a multiple well field with M fully penetrating wells which is intersected by a hyraulically connected stream as shown in Figure 3.1. Let the irregular grid system divide sections of the aquifer having different values of transmissivity and storage coefficient. Let there be a real or imagined well which may be pumping, or recharging, at the center of each of these subdivided sections. The aquifer is assumed to be of infinte areal extent, and of uniform thickness, and the groundwater flow is approximately two-dimensional.

Under these assumptions, by using the linear systems theory the drawdown in the k^{th} well at a distance x from the river can be expressed as



(a) PLAN VIEW



(b) SECTION - XY

GL = GROUND LEVEL
GWT = GROUNDWATER TABLE
NPL = NONPUMPING LEVEL

PS = PIEZOMETRIC SURFACE
CL = CONFINING LAYER (SEMI-PERMEABLE)
L = LEAKAGE

Figure 3.1 General Aquifer System

$$s(x,k,t) = \sum_{j=1}^{M} \int_0^t q(j,t-\tau)U(k,j,\tau)d\tau + \int_0^t \frac{\partial h(t-\tau)}{\partial t} P(x,k,\tau)d\tau \qquad (3.1)$$

where, $s(x,k,t)$ is the drawdown in the k^{th} well located at a distance x from the river at time t (L), $q(j,t)$ is the pumping rate in the j^{th} well at time t ($L^3\ T^{-1}$), $h(t)$ is the stage in the river at time t (L), $U(k,j,t)$ is the unit impulse response function of the k^{th} well due to pumping at the j^{th} well at time t (L^{-2}), $P(x,k,t)$ is the unit step response of the k^{th} well located at a distance x from the river at time t (dimensionless), and M is the number of wells.

The initial condition on the drawdown is that there is no previous development, i.e., $s(x,k,0) = 0$. The boundary condition is specified by assuming zero drawdown at infinity for any time t.

Equation 3.1 can be written in a modified and discretized form as

$$s(x,k,N) = \sum_{j=1}^{M} \sum_{i=1}^{M} q(j,N-i+1)\beta(k,j,i) + \sum_{i=1}^{N} \Delta h(N-i+1)\beta_R(x,k,i) \qquad (3.2)$$

where, N is the N^{th} observation, $\beta(k,j,i)$ is the aquifer response coefficient of the k^{th} well at the i^{th} time step due to pumping from j^{th} well ($T\ L^{-2}$), $\Delta h(i)$ is the change in the stream stage at the i^{th} time step (L/T), and $\beta_R(x,k,i)$ is the stream-aquifer response coefficient of the k^{th} well located at a distance x from the stream at time t (dimensionless).

In Equation 3.2, the β-coefficients are related to the well radius, the distance between the wells, the transmissivity and the storage coefficient of the subsections (Figure 3.2), the initial conditions, the boundary conditions, the time period since the start of pumping and the theoretical relationship governing the aquifer flow system. The β_R-coefficients are based on the distance from the river to the point of observation, the aquifer diffusivity, the initial and boundary conditions of the stream, the time period from the start of pumping and the theoretical relationship governing stream-aquifer interaction.

The relationship shown in Equation 3.2 is general and can be used to solve different types of aquifer flow systems after making suitable simplifications. Several applications are illustrated in the detailed report. Some of these are: the stream-well-aquifer system with vertical leakage and the multiple well system without vertical leakage.

B) Modeling Technique

It is evident from the general theoretical formulation (Equation 3.2) that the drawdown at any point in an aquifer system is dependent on the historical record of pumping rates, stream stages, drawdowns and the magnitudes of the response coefficients, $\beta(k,j,i)$ and $\beta_R(x,k,i)$. These response coefficients are based on the physical characteristics of the stream-well-aquifer system, the transmissivity and the storage coefficient values, the theoretical relationships governing the aquifer flow system and the time elapsed since the beginning of pumping. Therefore, for a particular stream-well-aquifer system and a given time increment of pumping, the coefficients $\beta(k,j,i)$ and $\beta_R(x,k,i)$ can be considered to be constants.

Based on the foregoing discussion, in the present modeling technique, the aquifer response coefficients (β and β_R values) are first computed by using the historical record of drawdowns, pumping rates and stream stages. This phase is designated "calibration" of the model. The second phase is the "prediction" of aquifer response due to future pumping rates, variations in river stage, etc. The results obtained during the calibration phase are used for predicting future drawdowns.

The study revealed that this modeling technique has several advantages over the conventional finite difference technique. For example, the locations of the existing and the planned wells constitute the number of nodes in the model, thus reducing the number of simultaneous equations and hence the computational time. The final transmissivity and the storage coefficient values at each nodal point are not required in this technique.

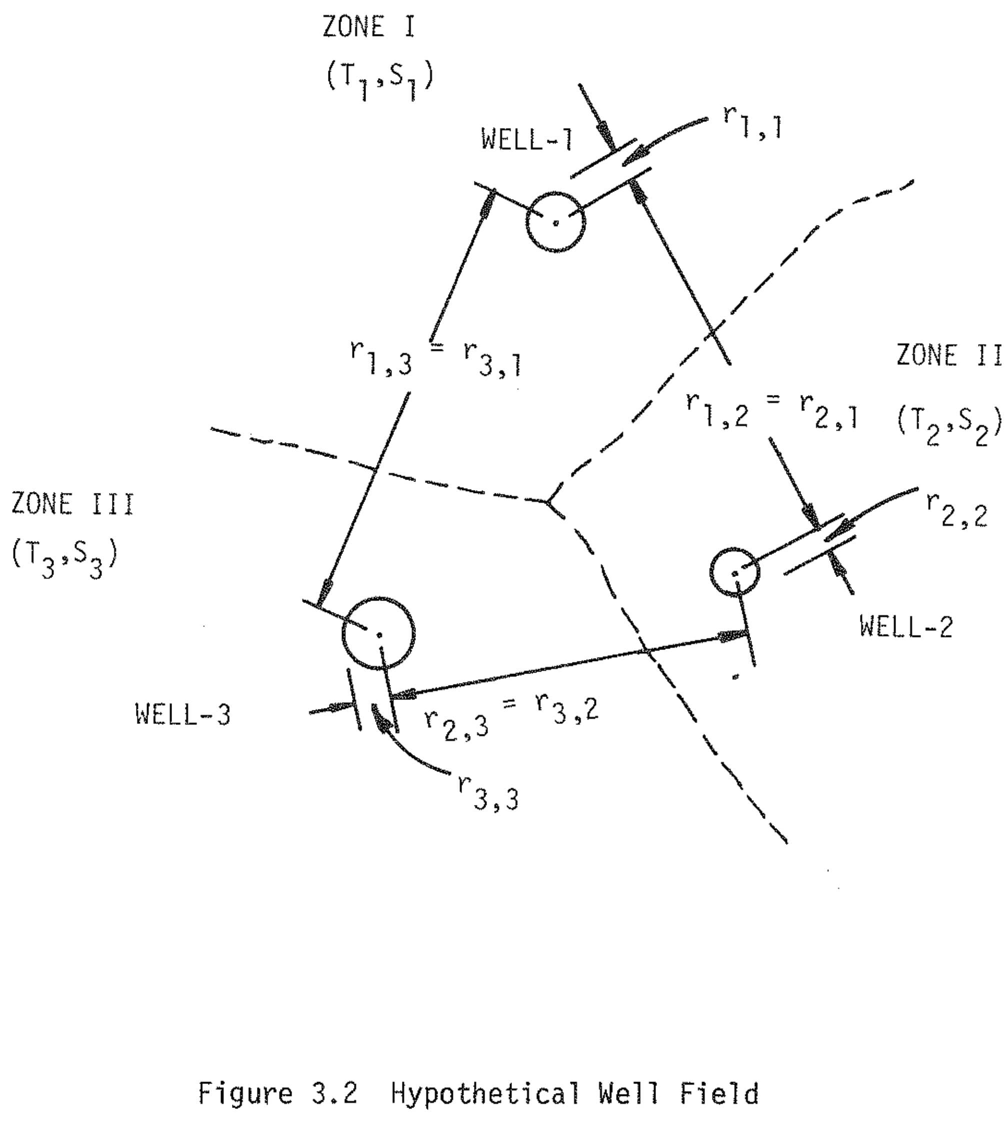


Figure 3.2 Hypothetical Well Field

3.4 CASE STUDIES - LINEAR SYSTEM MODELS - DETERMINISTIC APPROACH

The principal case studies as described in the detailed report are listed in Table 3.2 below.

3.5 CONCLUSIONS - LINEAR SYSTEM MODELS - DETERMINISTIC APPROACH

The procedure discussed in the present study has several advantages over other commonly used methods. A few of these advantages are briefly described below.

1) In the present method, the locations of the existing and the planned wells constitute the number of nodes in the model. Consequently, the number of simultaneous equations to be solved at each observation is drastically reduced. The number of nodes increased only with the number of wells, and is independent of the areal extent of the aquifer.

2) As the number of nodes used in the present method is small compared to that in a finite difference model of the aquifer, the time required to determine and specify the input data at each nodal point is also much smaller in comparison with the corresponding effort in a finite difference model.

3) Unlike other deterministic models, the predetermined aquifer transmissivity values are not used as inputs in the present procedure. However, estimated storage coefficient values are used as one of the inputs. It is relatively easy to estimate the the storage coefficients after examining the geology

4) A trial and error procedure is used to arrive at satisfactory solutions in both the traditional and the present methods. However, the number of trials needed in the present procedure are fewer than those required in an R-C network or a finite difference model. Consequently, the computational expenditure is drastically reduced in the present procedure.

5) The present procedure is analogous to the finite element method, in the sense that the nodal points can be spaced at irregular intervals.

6) The deterministic relationships, such as the Theis nonequilibrium equation and the stream-aquifer interaction formulas, which were used to analyse the ground water flow problems in the present study are easier to program for a digital computer than the finite difference equations. Consequently, the complexity of the problem is considerably reduced in the present formulation.

Based on the foregoing discussion, the present procedure is a simple and less expensive method for the analysis of regional aquifer problems.

3.6 CAUSALITY AND THE CONSTRUCTION OF STOCHASTIC MODELS FOR GROUNDWATER LEVELS

Groundwater levels are affected by hydrologic processes such as precipitation, evapotranspiration and river stage. Therefore, these variables are necessary as inputs in formulating models for the evaluation of groundwater resources. A preliminary investigation of the nature of the relationship between groundwater levels and these causal variables will be of considerable help in introducing them appropriately into groundwater models. Usually these causal relationships are investigated by examining time series plots, by gross water budget analysis or by cross correlation studies. However, these methods may not yield reliable information under certain circumstances such as when water levels are at a great depth below the ground

Table 3.2 Groundwater Case Studies

1. Multiple well system in homogenous aquifer	Pike County, Illinois
2. Pumping test analysis	Milton, Illinois Gridley, Illinois Grand Island, Nebraska
3. Stream-Aquifer Interaction without pumping	Kankakee R, Indiana
4. Regional Aquifer	Hypothetical Problem

surface. Some statistical methods are used to investigate these causal relationships. Stochastic models are also developed for the prediction of groundwater levels using past groundwater levels, precipitation and river stage data.

3.7 METHODOLOGY - STOCHASTIC MODELS

The stochastic difference equation models of hydrologic or meteorologic processes such as precipitation, temperature, streamflow and stream stages are considered. The general form of the stochastic difference equation which can be used to model the above processes is discussed below.

Let Y(k) represent the monthly value of variate Y at the k^{th} instant, k = 1,2,3,...,N. Let the variate Y be significantly correlated with the other variates, say X and Z. In a physical sense, the variate Y may represent the mean monthly stages in a river, whereas the variates X and Z may represent the mean rainfall and the mean monthly groundwater levels in the vicinity of the stream gaging station. A general representation for Y(k) is a stochastic difference equation which relates Y(k) to its past values, Y(k-1), Y(k-2),... and the past values of the variates X and Z as shown in Equation 3.3.

If the variate Y exhibits significant periodicities, then it is customary to include the sinusoidal trend functions in the stochastic difference Equation 3.3 as

$$Y(k) = \alpha_0 + \sum_{j=1}^{n_0} \alpha_j \, Y(k-j) + \sum_{j_1=1}^{n_1} \alpha_{j_1} \, X(k-j_1)$$

$$+ \sum_{j_2=1}^{n_2} \alpha_{j_2} \, Z(k-j_2) + \sum_{j_3=1}^{n_3} \alpha_{j_3} \, W(k-j_3)$$

$$+ \sum_{j_4=1}^{n_4} \left[\beta_{j_4} \sin\left(\frac{2\pi j_4 k}{12}\right) + \gamma_{j_4} \cos\left(\frac{2\pi j_4 k}{12}\right)\right]$$

$$+ W(k), \qquad (3.3)$$

where, $n = n_0+n_1+n_2+n_3+1$ = the total number of parameters, and W(.) = independently and identically districbuted random variables with zero mean.

The unknown coefficients α_j, β_j and γ_j, j = 1, 2, ... and the integers n_i, i = 0, 1, 2, ... (Eq. 3.3) can be estimated from the given observations y(k), k = 1, 2, ... N using a suitable criterion of performance. In the present study the least square criterion is selected. The method used for parameter estimation is discussed in Kashyap and Rao*.

3.8 CASE STUDIES - STOCHASTIC MODELS

Monthly values of rainfall, river stages and groundwater levels observed at Lafayette and West Lafayette, Indiana, were used in the present study.

Rainfall data are recorded at several gaging stations in Lafayette and West Lafayette. In the present study, the rainfall data measured only at two gaging stations are considered for analysis. These stations are, (i) the Purdue Agronomy Farm, West Lafayette and (ii) the O'Neall Farm, Lafayette. The location of these two gaging stations are shown in Fig. 3.3. The rainfall data from the Agronomy Farm are available since 1954 and that at the O'Neall Farm dates back to 1918. The monthly rainfall data from these stations were obtained from the publications, "Climatological Data," of the U.S. Department of Commerce.

The river stage data used in this study were those observed at the Wabash River which separates the twin cities, Lafayette and West Lafayette as shown in Fig. 3.3. The stage gage is located in Lafayette (Fig. 3.3) with the datum of the gage at 504.14 ft. above mean sea level. The mean monthly stages of the Wabash River were collected from the "Daily River Stages" (Weather Bureau, U.S. Department of Commerce) and the data dates back to 1914.

Several observation wells are used in Lafayette and West Lafayette by the U.S. Geological Survey to measure groundwater levels. Although these wells are never used for pumping, the static water levels measured from these wells are significantly affected by pumping in neighboring wells. The water levels from these wells are measured with reference to the land surface datum at irregular time intervals and are published in Water-Supply Papers

Kashyap, R. L. and Rao, A. R., "Stochastic Dynamic Models for Emperical Data," Academic Press, New York, 1976.

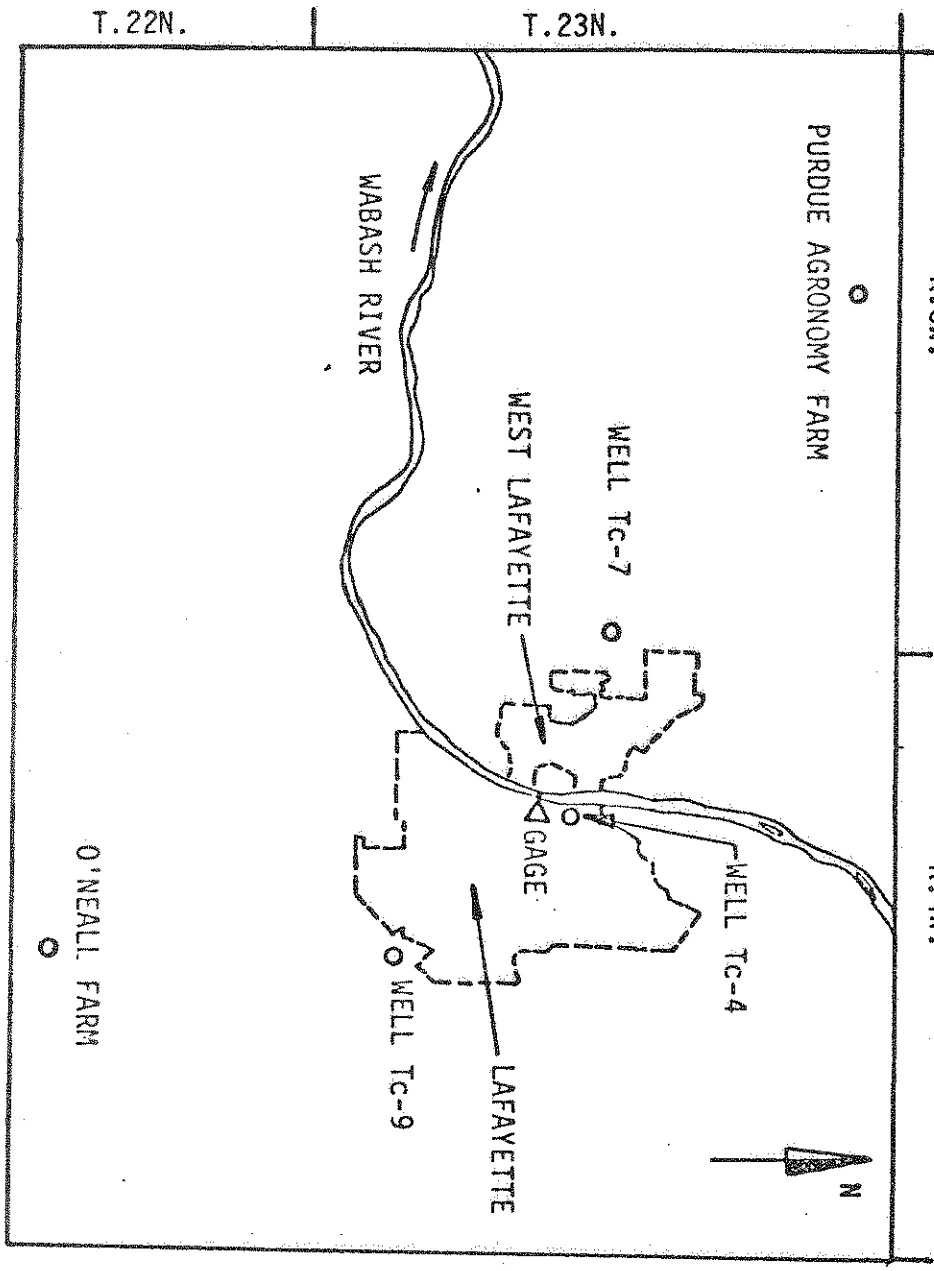


Figure 3.3 Location of Stations

(U.S. Geological Survey). These water levels were averaged over a month to obtain monthly values. In this study, the monthly average values of groundwater levels measured only at three observation wells are considered for analysis. The location of these wells are shown in Fig. 3.3 and are designated Tc-4, Tc-7 and Tc-9. Observation well Tc-4 is located in Lafayette and is very close to the Wabash River. Wells Tc-7 and Tc-9 are respectively situated in West Lafayette and Lafayette and both are away from the Wabash River. Details of these observation wells, the values of the land surface datum and the period of available data are given in Table 3.3.

A) Statistical Characteristics of the Data

Some of the elementary statistics of the hydrologic data used in this analysis are presented in Table 3.4

The monthly means of the precipitation data, the Wabash River stages and the water levels in well Tc-4 change over the year. Consequently, a seasonal pattern exists in the above processes. However, the monthly means of water level data from wells Tc-7 and Tc-9 are fairly constant over the year and do not exhibit any pronounced seasonality. The monthly standard deviations of the Wabash River stages and of the water levels in well Tc-4, Tc-7 and Tc-9 exhibit pronounced seasonal patterns. The seasonal patterns of the monthly standard deviations of the precipitation data are not clearly preceptible.

The autocovariances and the power spectra of the data used in the study were also examined. The correlograms of observed precipitation data from both the stations indicate the presence of an annual cycle. The prominance of the annual cycle is also apparent in the power spectral density plots of the precipitation data. The correlograms and power spectral densities of the Wabash River stages and of the water levels in well Tc-4 indicate the existence of strong annual periodicity and some concentration of power at low frequencies. The water level data observed from wells Tc-7 and Tc-9 do not show any significant annual periodicities as evident from their correlograms and power spectral density plots. The comparatively strong annual cycle in well Tc-4 may be attributed to its proximity to the Wabash River. The correlograms of the observed water levels in wells Tc-7 and Tc-9 indicate the highly correlated nature of the respective water levels.

The above results regarding the correlograms and the power spectral densities of the observed data clearly indicate that the models fitted to the observed data must account for the annual periodicities and the low frequency effects.

The cross correlation among the time series of the groundwater levels, precipitation and the Wabash River stages are examined. These cross correlograms indicate that the groundwater levels in the Lafayette-West Lafayette area are significantly correlated with the precipitation series in the sense that these cross correlation coefficients are higher than the 2-standard error limits at several lags. For example, the water levels in well Tc-7 are significantly correlated with the precipitation at the Agronomy Farm at a positive lag of 20 months and at negative lags of 9 to 21 months. However, the highest cross correlation between these water levels and precipitation is about 0.18 at a lag of about 9 months, which indicates that the present change in groundwater levels is primarily influenced by the rainfall that had occurred about nine months previously.

The cross correlograms of the groundwater levels and the Wabash River stages indicate the highly periodic relationship between the different hydrologic variables considered in the study. The cross correlogram between water levels in well Tc-4 and the Wabash River Stages indicates significant positive correlations at lags of 1, 12 and 24 months, and negative correlations at lags of 6, 18 and 30 months. However, the cross correlation at lag zero is the most predominant of all, which indicates that the well Tc-4 responds to the river stages within a few days. The cross correlograms for water levels in well Tc-7 and well Tc-9 also show significant correlations with the Wabash River stages. As these wells are located far away from the Wabash River, these cross correlograms exhibit certain lag period, which indicates that the present change in water levels at these wells is

Table 3.3 Details of Hydrologic Data

DATA	Measured at	Location Details	Symbol Used in the Text	Datum (Ft. above M.S.L)	Duration of Data: Available	Duration of Data: Used in the study	Source of Data and Remarks
1	2	3	4	5	6	7	8
Rainfall	Purdue Ag. Farm W. Lafayette, IN	Lat: 40°28'N. Long: 87°00'W.	AGF		1954-present	1954-'73	Climatogical Data U.S. Dept. of Commerce
Rainfall	O'Neall Farm Lafayette, IN	Lat: 40°21'N.	ONF		1918-present	1947-'62	Climatogical Data U.S. Dept. of Commerce
River Stages	Wabash River, Lafayette, IN	Gage at Brown St. Levee, Laf.	WAB	504.14	1914-present	1954-'73	Daily River Stages U.S. Weather Bureau stage measured above datum.
Groundwater Levels	Well Tc-4 Lafayette Water Works, Lafayette Unused drilled well, dia. 12", depth 127 ft.	T23N, R4W, Sec. 20 NE¼ SW¼ NE¼ East bank of Wabash River near Canal St. Well 7 at City Well Field	H1	520.87	1944-present	1954-'73	U.S.G.S. Water Supply Papers "Groundwater Levels in Northeastern States". Water levels reported as depths below land surface datum.
Groundwater Levels	Well Tc-7 Purdue Univ. W. Lafayette Abandoned drilled well, dia. 8", depth 206.5 ft.	T23N, R5W, Sec. 13 SE¼ SE¼ Research Housing pumphouse.	H2	679.00	1945-present	1954-'73	
Groundwater Levels	Well Tc-9 Aluminum Co. of America, Laf. Drilled unused well, dia. 16", depth 160 ft.	T23N, R4W, Sec. 34 NW¼ NW¼ Earl Ave & U.S. Highway 52	H3	662.00	1947-1962	1947-'62	

Table 3.4 Statistics of Data Used in Stochastic Models

STATISTIC	PRECIPITATION (IN)		WABASH RIVER STAGES (Ft. above datum)	GROUNDWATER LEVELS (Ft. below Land Surface Datum)		
	PURDUE AG. FARM	O'NEALL FARM		Well Tc-4	Well Tc-7	Well Tc-9
Period of Data	1954-'73	1947-'62	1954-'73	1954-'73	1954-'73	1954-'62
Mean	3.28	3.28	4.64	16.61	168.06	73.96
Variance	4.04	3.88	9.21	22.26	4.28	3.46
Skew. Coeff.	1.05	1.16	0.98	0.64	0.13	0.51
Coeff. of Kurtosis	4.23	4.87	3.04	5.20	2.58	3.18
Minimum	0.08	0.12	0.40	1.40	168.23	69.85
Maximum	11.70	11.60	13.80	33.60	173.25	80.08
Median	2.72	2.91	3.60	16.50	168.23	73.90

influenced by the Wabash River stages that was observed several months previously.

B) Univariate Models for Groundwater Levels, Precipitation and River Stages

In this section, univariate models of the form of relationship shown in Eq. 3.3 are fitted to groundwater levels, precipitation and river stages. For example, a univariate model for Wabash River stages is formulated by using its past values and appropriate sinusoidal trend functions representing the predominent periodicities. The best fitted univariate models for the groundwater levels, precipitation and the river stages are presented in Table 3.5.

The whitened process derived from the univariate models listed in Table 3.5 were tested for the causal relationship between precipitation, river stages and groundwater levels. The tests are given in the detailed report. The conclusion of the tests are that the residuals from model H2 (see Table 3.5) for water levels in well Tc-7 are significantly correlated at lags 1, 8 and 15 months with the residuals of model AGF for precipitation at the Agronomy Farm. These correlations should be incorporated in model H2 to arrive at a final model for water levels in well Tc-7. Likewise, there are significant correlations between the residuals of model H2 and those of model WAB at lags 1, 10, 15 and 17 months.

Consequently, two different final models are formulated for water levels in well Tc-7. The first of these (Eq. 3.4) is constructed using the univariate model H2 and the model resulting from the causal relationship with the residuals of model AGF for precipitation at the Agronomy Farm. The second model (Eq. 3.5) is the combination of model H2 and the model obtained for the causal relationship with the residuals of model WAB for the Wabash River stages.

The final stochastic model for water levels in well Tc-7 are:

$$\begin{aligned} y(k+1) = {} & 2.772 + 1.310\, y(k) - 0.351\, y(k-1) \\ & + 0.025\, y(k-10) + 0.019 \operatorname{Sin} \omega_1 k \\ & - 0.187 \cos \omega_1 k + W_A(k) + 0.0168\, W_A(k-7) \\ & + 0.0222\, W_A(k-14) + \eta_{YA}(k+1) \end{aligned} \tag{3.4}$$

where the $\eta_{YA}(.)$ are the residuals.

The second stochastic model for water levels in well Tc-7 which takes into account the effect of the Wabash River stages is

$$y(k+1) = 2.772 + 1.310\ y(k) - 0.351\ y(k-1) + 0.025\ y(k-10) + 0.019\ \text{Sin}\ \omega_1 k - 0.187\ \text{Cos}\ \omega_1 k + 0.0139\ W_S(k) + 0.0182\ W_S(k-9) + 0.0194\ W_S(k-14) - 0.0167\ W_S(k-16) + \eta_{YS}(k+1) \quad (3.5)$$

where η_{YS} is the residual.

c) Conclusions - Stochastic Models

Three different models, viz. H2, HHX and HHY were fitted to the water levels in well Tc-7 in West Lafayette. The first of these was a univariate model (Table 3.5) and the second model (Eq. 3.4) was developed after incorporating the causal relationship between the residuals of univariate model H2 and those of univariate model AGF for rainfall at the Agronomy Farm. The model given in Eq. 3.4 has been formulated after considering the causal relationship between the residuals of univariate model H2 and those of univariate model WAB for the Wabash River stages.

The statistical characteristics of the simulated sequences of models (Eqs. 3.4 and 3.5) were in close agreement with those of the observed data. In particular, the higher order properties such as coefficients of skewness and kurtosis were also preserved in these simulated sequences. Consequently, these models in Eqs. 3.4 and 3.5 developed after considering the causal relationships are superior to the model H2.

An added advantage of these two models for generating synthetic sequences of groundwater levels is in simulation. For example, models for groundwater levels are formulated by using rainfall as one of the inputs (Rao et.al., 1975). A general form of this model is given as

Table 3.5 Univariate Models Fitted to Monthly Groundwater Levels, Precipitation and River Stages

SYMBOL	DATA	STATION	MODEL
AGF	Precipitation	Purdue Agronomy Farm	$y(k+1) = 3.016 + 0.024\ y(k) - 0.016\ y(k-1) + 0.232\ \text{Sin}\ \omega_1 k - 1.160\ \text{Cos}\ \omega_1 k - 0.042\ \text{Sin}\ \omega_2 k - 0.202\ \text{Cos}\ \omega_2 k + W_A(k)$
ONF	Precipitation	O'Neall Farm	$y(k+1) = 2.944 + 9.986\ y(k) + 0.022\ y(k-1) + 0.594\ \text{Sin}\ \omega_1 k - 0.804\ \text{Cos}\ \omega_1 k - 0.297\ \text{Sin}\ \omega_2 k - 0.019\ \text{Cos}\ \omega_2 k + W_B(k)$
WAB	River Stages	Wabash River at Lafayette	$y(k+1) = 3.270 + 0.253\ y(k) + 0.049\ y(k-1) + 1.427\ \text{Sin}\ \omega_1 k + 1.220\ \text{Cos}\ \omega_1 k - 0.022\ \text{Sin}\ \omega_2 k - 9.277\ \text{Cos}\ \omega_2 k + W_S(k)$
H2	Groundwater Levels	Well Tc-7*	$y(k+1) = 2.772 + 1.310\ y(k) - 0.351\ y(k-1) + 0.025\ y(k-10) + 0.019\ \text{Sin}\ \omega_1 k - 0.187\ \text{Cos}\ \omega_1 k + W_Y(k)$
H3	Groundwater Levels	Well Tc-9	$y(k+1) = 10.611 + 0.543\ y(k) + 0.028\ y(k-1) + 0.182\ y(k-2) - 0.135\ y(k-3) + 0.239\ y(k-4) + W_Z(k)$

$\omega_1 = 2\pi/12$, $\omega_2 = 2\pi/$ $W_A(k)$, $W_B(k)$, $W_S(k)$, $W_X(k)$, $W_Y(k)$, $W_Z(k)$ are residuals

*Final models given as Eqs. 3.4 and 3.5.

$$Y(k+1) = \alpha_0 + \alpha_1 Y(k) + \ldots + \beta_1 X(k) + \beta_2 X(k-1) + \ldots + \eta(k+1) \quad (3.6)$$

where, Y(.) and X(.) represent the groundwater level and rainfall processes respectively and $\eta(.)$ are the residuals. In the above model (Eq. 3.6), it is more difficult to simulate X(.) series than the random noise, $\eta(.)$ series. On the other hand, the final stochastic models, (Eqs. 3.4 and 3.5) are composed of the past values of groundwater levels and residual sequences such as $W_A(.)$, $\eta_{YA}(.)$, $W_S(.)$ and $\eta_{YS}(.)$. These residual sequences can be readily generated on a digital computer using the appropriate probability distributions. Consequently, the present formulation is better suited for generating synthetic sequences of groundwater levels.

The final stochastic model for water levels in well Tc-9 (Table 3.5) does not include any residuals from either precipitation or river stage models. The characteristics of the simulated data from this model were considerably different from those of the observed data. The aquifer in the vicinity of well Tc-9 is mostly under confined condition and hence the effects of the Wabash River stages and rainfall are considerably damped out. Consequently, these damped effects were not detected by the tests used for investigating the causal relationships.

3.9 PROJECT PUBLICATIONS

For further details regarding the groundwater investigation, the reader is referred to the following publications.

PWRC, Tech Rept 67, "Stochastic Models for Groundwater Levels," by A. R. Rao, R. G. S. Rao and R. L. Kashyap, August 1975, pg. 116, (Phase I).

PWRC, Tech Rept 72, "Regional Aquifer Evaluation Studies with Stochastic Inputs," by C. T. Bathala, J. A. Spooner and A. R. Rao, February 1976, pg. 85, (Phase I).

PWRC, Tech Rept 91, "Application of Linear Systems Analysis to Groundwater Studies," by C. T. Bathala, A. R. Rao, and J. A. Spooner.

Thesis, "The Application of Linear Systems Analysis to Groundwater Evaluation Studies," by C. T. Bathala, Ph.D. Thesis, August 1976, Dr. A. R. Rao, Major Professor.

C. T. Bathala, A. R. Rao and J. A. Spooner, "Linear System Models for Regional Aquifer Evaluation Studies," Proceedings, Applied Numerical Modelling, Conference held at the University of Southampton, July 1977, pp. 193-204, Pentech Press, London.

C. T. Bathala, A. R. Rao and J. A. Spooner, "Stochastic Models for Groundwater Relationships," Hydraulics in the Coastal Zone Proceedings, 25th Annual Hydraulics Division Specialty Conference, Texas A & M University, August 1977, pp. 211, abstract only, ASCE, 1977.

Chapter 4
Surface Water Hydrology - Effects of Urbanization on Low Flows and Total Runoff

4.1 INTRODUCTION

As the percentage of built-up or impervious surface within a watershed increases, more and more precipitation falling on the area becomes direct runoff. This reduces the quantity of water available to replenish the soil moisture and the groundwater storage. The flow volumes in the stream are then reduced due to the diminished groundwater supply. On the other hand, in many urbanized areas, the effluent from sewage and industrial treatment plants may become a major portion of the low flow in the stream. In some cases, the low flow volumes have actually increased because of this.

In view of these considerations, the following objectives were selected for this portion of the study.

Objective I

To investigate the effects of urbanization on the low flow characteristics of streams.

Objective II

To investigate the effects of urbanization on total runoff and water yield.

The study was primarily directed to the analysis of annual, 1- and 7-day low flows and the annual total runoff from six urban basins. Table 4.1 lists the watersheds, the locations of the streamgaging stations, and the rainfall stations and the basin areas.

4.2 MASS CURVES AND FLOW DURATION ANALYSIS

Mass curves were developed with annual 1- and 7-day low flows and total runoff. The year in

Table 4.1 Location of Streamgaging and Rainfall Stations Used in the Study

Stream Name	USGS ID Number	Location	Basin Area [mi^2]	Period of Records
Boneyard Creek	03337000	Champaign, IL	4.70	Oct. 1948 - Sept. 1974
East Meadow Brook	01310500	Freeport, NY	31.00	Oct. 1937 - Sept. 1974
Pleasant Run	03353160	Indianapolis, IN	10.10	Oct. 1960 - Sept. 1974
Ralston Creek	0545500	Iowa City, IA	3.01	Oct. 1924 - Sept. 1974
Salt Creek	05531500	Western Springs, IL	114.00	Oct. 1945 - Sept. 1974
Waller Creek	08157500	Austin, TX	4.13	Oct. 1955 - Sept. 1974

Streamgaging Stations

Stream Name	City	County	Latitude	Longitude
Boneyard Creek	Urbana, IL	Champaign	40° 06'	88° 14'
East Meadow Brook	New York, NY	New York	40° 47'	73° 58'
Pleasant Run	Indianapolis, IN	Marion	39° 46'	86° 06'
Ralston Creek	Iowa City, IA	Johnson	41° 39'	91° 32'
Salt Creek	Chicago, IL	Cook	41° 59'	87° 54'
Waller Creek	Austin, TX	Travis	30° 18'	97° 42'

Rainfall Stations

which the mass curves began to substantially change their slopes indicates the time at which some natural or man-made changes took place within the watershed which altered the pattern of the observed flows.

The years in which the change of slopes of the mass curves occurred served to divide the observed flow data into two periods, one in which the effects of urbanization were not present and another in which they were. In the present study, the period preceding the year of change will be referred to as the 'unaffected' period. The period following the year of change will be referred to as the 'affected' period. The possibility of a change in the amount of rainfall was also studied by the same method. The results are summarized in Table 4.2. They show that the changes in mean annual rainfall are much less than the corresponding changes in the flow sequences.

Conventional flow-duration analysis was used to examine the extent of the changes in the daily flows. First, flow-duration curves were constructed for the unaffected, affected and entire periods by using average daily data. Several values of probability of exceedence were chosen and the corresponding flows were obtained by using the flow-duration curves. The results of this procedure are shown in Table 4.3 and indicate that the daily flows in Salt Creek, Pleasant Run, Ralston and Boneyard Creeks show increases in their daily flows given a specific probability of exceedence. Daily flows in Waller Creek and East Meadow Brook show decreases in their daily flows. These results confirm the findings of mass curve analysis.

4.3 CHANGES IN ANNUAL RAINFALL-RUNOFF RELATIONSHIPS

The rainfall-runoff relationships for each watershed were analyzed in order to determine the extent of changes in the total annual runoff. The analysis was accomplished by linearizing the rainfall-runoff relationships by the transformations developed by Box and Cox*. The slopes of the relationships for the 'unaffected' and 'affected' periods were compared to determine the magnitude of the changes which had taken place. The results from this analysis compared well with the percent changes computed directly from the observed data. Flows in Boneyard Creek, Pleasant Run, Ralston and Salt Creeks all showed increases in the quantity of runoff during the 'affected' period while those from East Meadow Brook and Waller Creek showed decreases. The percentages of change in runoff computed from the model and from the observations are listed in Table 4.4.

4.4 STATISTICAL ANALYSIS

As discussed in previous section, the 1- and 7-day low flows and the total annual runoff of the six urban streams have changed. It was also shown that these changes in runoff occurred even when the annual rainfall did not significantly change during the entire period. The purpose of the statistical analyses is to determine whether these changes in runoff are statistically significant. The magnitude of the changes are examined by comparing the means and variances of the observed flows in both the 'unaffected' and 'affected' periods in each stream. Next, the correlation structure of the observed flow sequences is to be analyzed in order to determine whether or not these sequences are uncorrelated. The flow sequences which are random are then subjected to well-known significance tests in order to determine the statistical significance of the changes in runoff characteristics. The statistical significance of the changes in the nonrandom flow sequences are tested by other methods. Table 4.5 shows the statistics of the observed flows.

The correlation structures of the observed flows were analyzed in order to determine whether the flow sequences represent random events. All the flows of the East Meadow Brook and the 1- and 7-day low flows of Salt Creek were found to be significantly autocorrelated. All the other flow sequences were found to be random, as shown in the last column of Table 4.5. For the random flow sequences, the magnitudes of the changes in the observed flow sequences were tested for significance. The null hypothesis for the u-test, the double sample t test,

**Box, B. E. P., and Cox, D. R., "An Analysis of Transformations," Jour. of Royal Statistical Society, Series B, Vol. 26, pp. 211-243, 1964.*

Table 4.2 Unaffected and Affected Period Mean Flows and Rainfalls

Stream and Observed Flows	Unaffected Period	Affected Period	Percent Change
Boneyard Creek	1949-1960	1960-1974	
Mean 1-day Low Flow	.81	.89	+ 9.9
Mean 7-day Low Flow	7.46	7.09	- 4.9
Mean Total Runoff	1682.5	1586.1	- 5.7
Mean Rainfall	36.51	38.33	+ 4.9
East Meadow Brook	1938-1962	1963-1974	
Mean 1-day Low Flow	7.96	1.71	- 78.5
Mean 7-day Low Flow	59.72	13.63	- 77.2
Mean Total Runoff	6354.1	3387.1	- 46.7
Mean Rainfall	44.13	44.76	+ 1.4
Pleasant Run	1961-1968	1969-1974	
Mean 1-day Low Flow	0	.19	-
Mean 7-day Low Flow	1.42	3.41	+ 140.1
Mean Total Runoff	2816.2	4060.7	+ 44.2
Mean Rainfall	35.85	38.65	+ 7.8
Ralston Creek	1925-1960	1961-1974	
Mean 1-day Low Flow	.01	.09	+ 800.0
Mean 7-day Low Flow	.05	.76	+1420.0
Mean Total Runoff	527.9	849.2	+ 60.9
Mean Rainfall	32.92	37.49	+ 13.9
Salt Creek	1946-1955	1956-1974	
Mean 1-day Low Flow	3.45	14.77	+ 328.1
Mean 7-day Low Flow	50.22	122.77	+ 144.5
Mean Total Runoff	30637.	48884.	+ 59.6
Mean Rainfall	34.23	35.99	+ 5.1
Waller Creek	1956-1962	1963-1974	
Mean 1-day Low Flow	.65	.53	- 18.5
Mean 7-day Low Flow	5.43	4.60	- 15.3
Mean Total Runoff	1342.3	1281.8	- 4.5
Mean Rainfall	32.30	32.84	+ 1.7

Table 4.3 Results of Flow-Duration Curve Comparisons

Stream	Probability of Exceedence	Unaffected Period Flow [cfs]	Affected Period Flow [cfs]	Percent Change
Boneyard Creek	.10	9.0	9.5	+ 5.5
	.20	4.5	5.5	+22.2
	.40	3.0	3.5	+16.7
East Meadow Brook	.10	28	16	-42.9
	.20	22	11	-50.0
	.40	17	7	-58.8
Pleasant Run	.10	19	24	+26.3
	.20	8	12	+50.0
	.40	3	6	+50.0
Ralston Creek	.10	3	5	+66.7
	.20	2	3	+50.0
	.40	1	2	+50.0
Salt Creek	.10	235	270	+14.9
	.20	125	160	+28.0
	.40	50	95	+90.0
Waller Creek	.10	5	4	-20.0
	.20	3	2	-33.3
	.40	2	1	-50.0

Table 4.4 Comparison of Percent Changes in Runoff

Stream and Flow Period	% Change in Runoff as Computed by Rainfall-Runoff Model	% Change in Runoff as Computed by Direct Calculation
Boneyard Creek		
Entire Period		
Unaffected Period		
Affected Period	18.6	-4.0
East Meadow Brook		
Entire Period		
Unaffected Period		
Affected Period	-40.0	-54.9
Pleasant Run		
Entire Period		
Unaffected Period		
Affected Period	5.41	+31.2
Ralston Creek		
Entire Period		
Unaffected Period		
Affected Period	28.0	+56.7
Salt Creek		
Entire Period		
Unaffected Period		
Affected Period	7.04	+21.2
Waller Creek		
Entire Period		
Unaffected Period		
Affected Period	-12.2	-20.1

Table 4.5 Statistics of Observed Flows

Stream and Flow Series	Entire Period $\overline{X}$	Unaffected Period $\overline{X}$	Affected Period $\overline{X}$	Percent Change	Entire Period σ^2	Unaffected Period σ^2	Affected Period σ^2	Percent Change	Random or Nonrandom
Boneyard Creek									
1-Day Low Flow	.85	.79	.90	+14.0	.0573	.0558	.0529	- 5.2	R
7-Day Low Flow	7.29	7.30	7.28	- .22	3.936	5.287	2.779	-47.4	R
Total Runoff	1637.99	1673.98	1607.13	- 4.0	1.04×10^5	1.297×10^5	7.997×10^4	-38.3	R
East Meadow Brook									
1-Day Low Flow	5.93	7.96	.87	-89.1	14.072	5.1657	.4379	-91.5	N
7-Day Low Flow	44.77	59.72	7.40	-87.6	722.278	215.966	32.830	-84.8	N
Total Runoff	5526.96	6554.08	2959.16	-54.9	4.02×10^6	1.61×10^6	1.61×10^6	+24.1	N
Pleasant Run									
1-Day Low Flow	.11	0	.25	-	.0271	0	.027	-	R
7-Day Low Flow	2.27	1.42	3.41	+140.8	8.305	11.86	1.293	-89.1	R
Total Runoff	3527.37	3110.79	4082.83	+ 31.2	1.38×10^6	1.23×10^6	1.03×10^6	-15.9	R
Ralston Creek									
1-Day Low Flow	.03	.005	.10	+1951	.0070	.0001	.0186	+18500	R
7-Day Low Flow	.25	.05	.76	+1519	.407	.011	1.058	+ 9518	R
Total Runoff	627.86	541.78	849.20	+56.7	1.34×10^5	86329	188360	+ 118	R
Salt Creek									
1-Day Low Flow	7.36	1.86	10.25	+451	38.067	.5324	33.5635	+ 6204	N
7-Day Low Flow	75.23	23.00	102.73	+347	2255.90	61.714	1218.92	+ 1875	N
Total Runoff	36929	32430	39279	+21.2	2.05×10^8	8.80×10^7	2.50×10^8	+ 184	R
Waller Creek									
1-Day Low Flow	.61	.74	.53	-29.0	.0639	.1310	.0077	-94.1	R
7-Day Low Flow	5.13	6.19	4.51	-27.1	4.223	8.847	.487	-94.5	R
Total Runoff	1320.02	1511.71	1208.20	-20.1	2.84×10^5	5.4×10^5	98177	-82.0	R

the likelihood ratio test and the conditional t test was that there is no difference between the unaffected and affected period mean flows. The null hypothesis for the equality of variance test was that the population variances for both unaffected and affected periods are equal. The results of the tests are summarized in Table 4.6.

In the last column of Table 4.6 the results of the testing procedures are placed in three categories as the null hypothesis H_o, that "there was no difference in the unaffected and affected period mean flows" is accepted (A), it is rejected (R), and no conclusion (N). Definite conclusions concerning the acceptance or rejection of the null hypothesis could not be arrived at due to conflicting results from the significance tests. The following tentative conclusions are presented based on the results of the tests. The null hypothesis may be accepted for the 1-day low flow sequences of Boneyard Creek, East Meadow Brook, Ralston and Salt Creek. The H_o could be neither accepted nor rejected for the 1-day low flows of Pleasant Run and Waller Creek because of conflicting results from the significance tests. As a result, none of the changes which have been seen in the 1-day low flow sequences can be considered significant according to the tests used. The null hypothesis is accepted for the 7-day low flows of Boneyard Creek, East Meadow Brook and Salt Creek. Therefore, the changes present in these flows were not considered significant. However, H_o was rejected for the 7-day low flows of Pleasant Run and Ralston Creek indicating that the changes in these flows were significant. No conclusion could be reached concerning the significance of the changes in the 7-day low flows of Waller Creek because of conflicting results in the significance tests. Finally, the results of the significance tests concerning the total annual runoff sequences indicate that the null hypothesis is accepted only for the Waller Creek sequence. H_o is rejected for

Table 4.6 <u>Statistical Tests</u>

BASIN and FLOW	U Test	Equality of Variances	Double Sample T Test	Likelihood Ratio Test	Conditional T Test	Global Evaluation
	Decision	Decision	Decision	Decision	Decision	Decision
Boneyard Creek						
1-Day Low Flow	A	A	A	A	A	A
7-Day Low Flow	A	A	A	A	A	A
Total Runoff	A	A	A	A	R	N
Pleasant Run						
1-Day Low Flow	-	-	R	A	-	N
7-Day Low Flow	R	A	A	R	R	R
Total Runoff	R	A	R	A	R	N
Ralston Creek						
1-Day Low Flow	R	R	R	A	A	A
7-Day Low Flow	R	R	R	R	R	R
Total Runoff	R	R	R	A	A	N
Salt Creek						
Total Runoff	R	A	R	R	R	R
Waller Creek						
1-Day Low Flow	A	A	A	A	R	N
7-Day Low Flow	A	A	A	A	R	N
Total Runoff	A	A	A	A	A	A

A - Null hypothesis is accepted R - Null hypothesis is not accepted N - No conclusion the total annual runoff sequences of East Meadow Brook and Salt Creek. The null hypothesis H_0 could be neither accepted nor rejected for the Boneyard Creek, Pleasant Run and Ralson Creek flow sequences because of conflicting results from the significance tests. We would like to emphasize again that as the number of observations were very small, the results of the statistical tests of significance cannot be accepted as being definitive.

4.5 CONCLUSIONS

On the basis of the analysis and the results presented in the foregoing sections the following conclusions may be presented.

1. The characteristics of the low flows, total runoff, and daily runoff are affected by the urbanization process.

2. The transformation technique presented by Box and Cox can be successfully used to linearize the rainfall-runoff relationships.

3. It was not possible to conclusively establish the statistical significance of the changes observed in the low flow and total runoff sequences because of the small number of available observations.

4.6 PUBLICATIONS

For further details on the effects of urbanization on low flow and total runoff the reader is referred to the following publications.

PWRRC Tech. Rept. 94, "The Effects of Urbanization on Low Flows and Total Runoff," by R. W. Shanks and A. R. Rao, May 1977.

Thesis: "The Effects of Urbanization on Low Flows and Total Runoff," by R. W. Shanks, MSCE thesis, July 1977, Dr. A. R. Rao, Major Prof.

A. R. Rao and R. G. S. Rao, "Analysis of the Effects of Urbanization on Runoff by Nonlinear Functional Series Model of Rainfall-Runoff Process," Proceedings, Intl. Symp. on Urban Hydrology, Hydraulics and Sediment Control, Univ. of Kentucky, July 1977, pp. 209-220.

R. W. Shanks and A. R. Rao, "The Effects of Urbanization on Low Flows and Total Runoff," Hydraulics in the Coastal Zone, Proc. of the 25th Annual Hydraulics Division Specialty Conference, Texas A&M University, Aug. 1977, pp. 203-210, ASCE, 1977.

Chapter 5

Development of an Extension of the ILLUDAS Model for Continuous Simulation of Urban Runoff Quantity and Discrete Simulation of Runoff Quality

5.1 INTRODUCTION

This portion of the study deals with the development of a short-time interval continuous simulation of the storm water runoff quantity and quality and its verification on the Upper Ross-Ade Watershed in West Lafayette, Indiana. The proposed model DRAINQUAL consists of an extension of the Illinois Urban Drainage Area Simulator, ILLUDAS, developed by the Illinois State Water Survey, coupled with a modification of the runoff quality subroutine of the Storage, Treatment, Overflow, Runoff Model STORM, developed by the Hydrologic Engineering Center of the Corps of Engineers in Davis, California.

The specific objective of this section was the development of an integrated rainfall-runoff-quality model of the design type, which uses a small computational time interval and that would yield detailed hydrographs and pollutographs.

5.2 MODEL DEVELOPMENT

The model ILLUDAS was selected for the modelling of the rainfall-runoff process because of its accuracy and flexibility. It operates either in the evaluation mode or in the design mode. In the evaluation mode it produces the outflow hydrograph resulting from a given single rainfall event. The calculations include the routing of the runoff resulting from the pervious and impervious areas through the sewer systems. In the design mode the program evaluates the necessary pipe and channel sizes to convey the flows resulting from the selected design storm. A detention storage may be specified at any point of the drainage network. The program also calculates the necessary storage when the pipe size is too small to carry the maximum discharge.

The model ILLUDAS has two basic limitations:

(1) there is no provision for continuous simulation;
(2) no runoff quality calculation, routing or reaction is incorporated into the program.

A substantial portion of the study was concerned with the elimination of these two limitations. However, before proceeding to such an objective it was necessary to study the response of the model ILLUDAS to changes and inaccuracies in the input through a sensitivity analysis.

From the sensitivity analysis it was concluded that a time increment not larger than the average inlet time of 5 minutes gave correct results (Fig. 5.1). The model is about equally sensitive to the proper selection of the soil group and of the antecedent moisture condition.

The ILLUDAS model was modified by including a subroutine which performs a continuous accounting of the antecedent soil moisture. With the inclusion of this subroutine the model can produce a continuous simulation of the runoff given a long-time series of rainfall events. The modified model was calibrated for the initial abstraction in the paved and grassed areas. The calibration used a series of 132 storms recorded at 5 minute intervals in 1970 in the Upper Ross-Ade Watershed. A series of 154 storms recorded at 5 minute intervals in 1974 as well as the dry periods between storms were used for verification. The results were compared with the observed runoffs and with the runoff values calculated at hourly intervals by the model STORM (Fig. 5.2). The errors using the ILLUDAS model were considerably less than those using the STORM model. The total runoffs from the Upper Ross-Ade Watershed were computed for 25 selected storms in 1970 with a mean runoff error of -5.7% by ILLUDAS, and -6.4% by STORM. For 6 selected storms in 1974, the mean runoff errors were +11.4% and -56.7% by ILLUDAS and STORM, respectively. The runoff coefficients were also calculated with a mean error of -3.7% and -23.9% by ILLUDAS and STORM, respectively, for the year 1970, and of +4.8% and -46.7% for the year 1974. The results also show that sixteen out of twenty-five storms in 1970 and four out of six storms in 1974, are better simulated by ILLUDAS than by STORM by comparing the percentage of error in the calculated runoff.

To add the runoff quality capability the sub-routine DIRT of the model STORM, which is written for a one hour interval was modified to simulate the runoff quality at 5 minute intervals. The modified sub-routine DIRT was then combined with the ILLUDAS program to form the DRAINQUAL model. Only the suspended solids and BOD were included in the program, as these pollution constituents were the only ones for which measurements were available in the Upper Ross-Ade Watershed. Comparison of the predicted and observed pollutographs show a fair agreement (Fig. 5.3). In all cases tested the calculated pollutograph by DRAINQUAL is considerably more accurate than that estimated by STORM.

5.3 PUBLICATIONS

For further details on the development of URBQUAL, the reader is referred to the following report.

PWRRC Tech. Rept. 109, "Development of an Extension of the ILLUDAS Model for Continuous Simulation of Urban Runoff Quantity and Discrete Simulation of Runoff Quality," by J. Han and J. W. Delleur, July 1979.

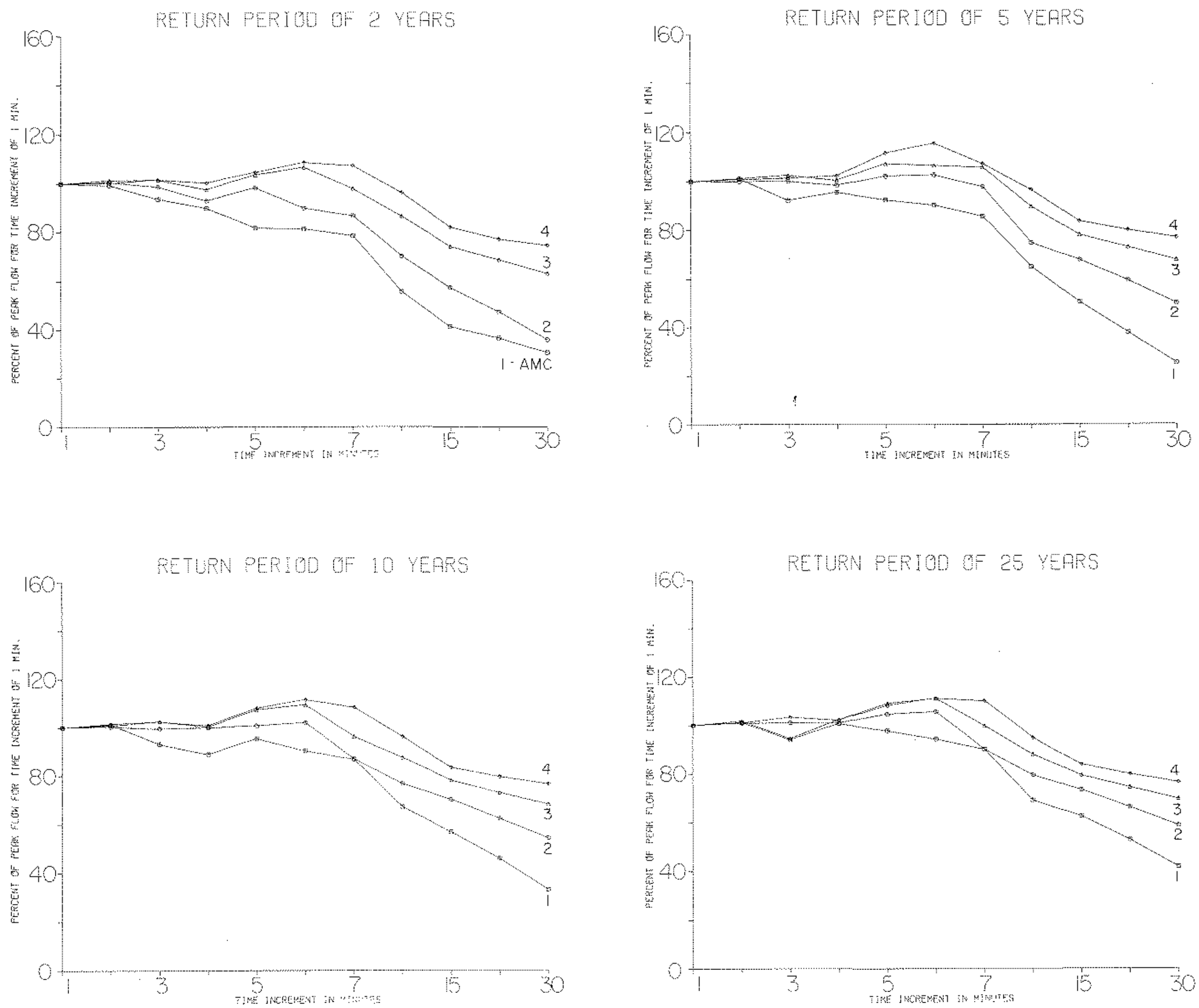


Figure 5.1 Sensitivity of Peak Flow to the Changes of Time Increments

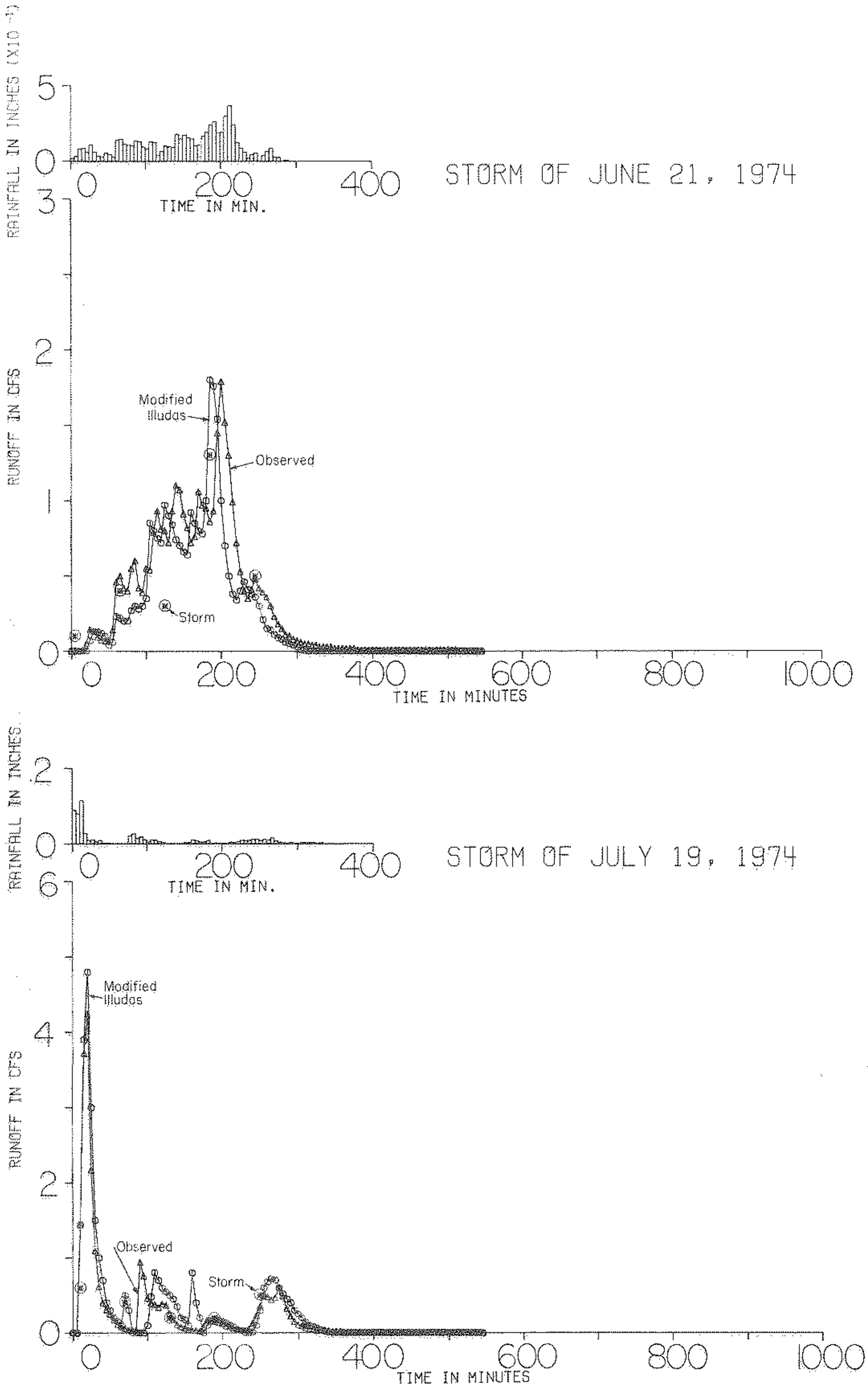
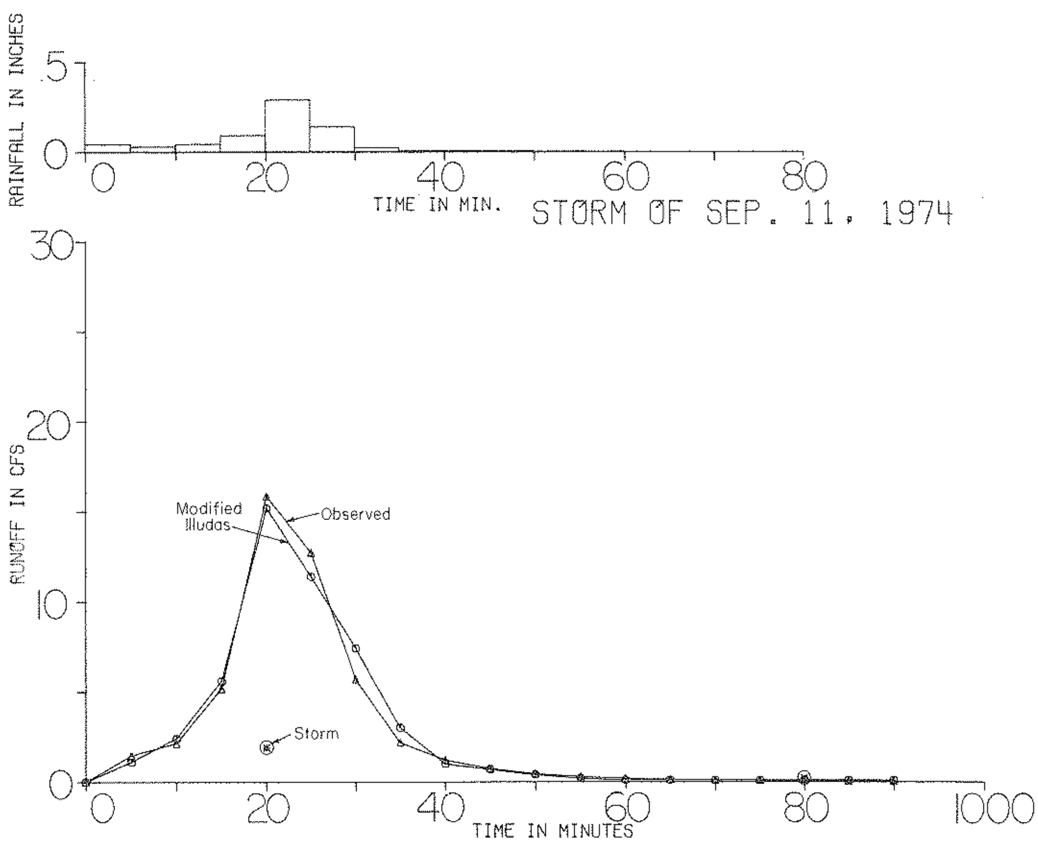


Figure 5.2 Observed and Calculated Hydrographs by the Modified ILLUDAS Model



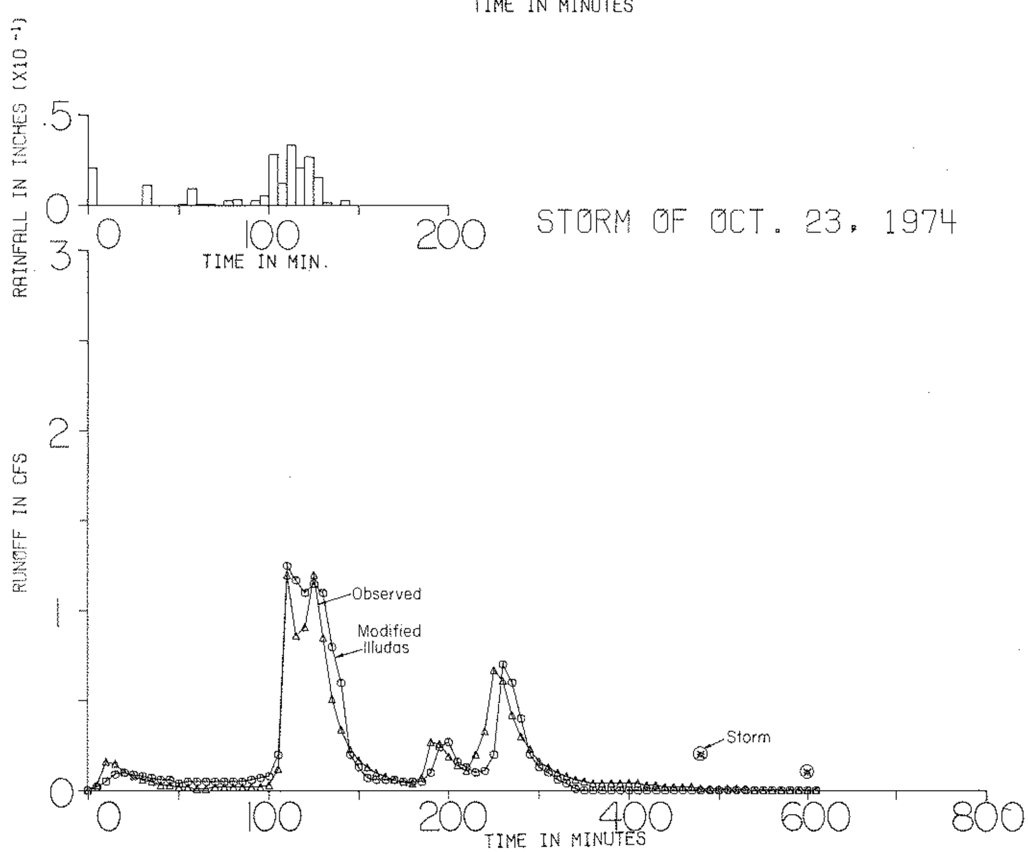
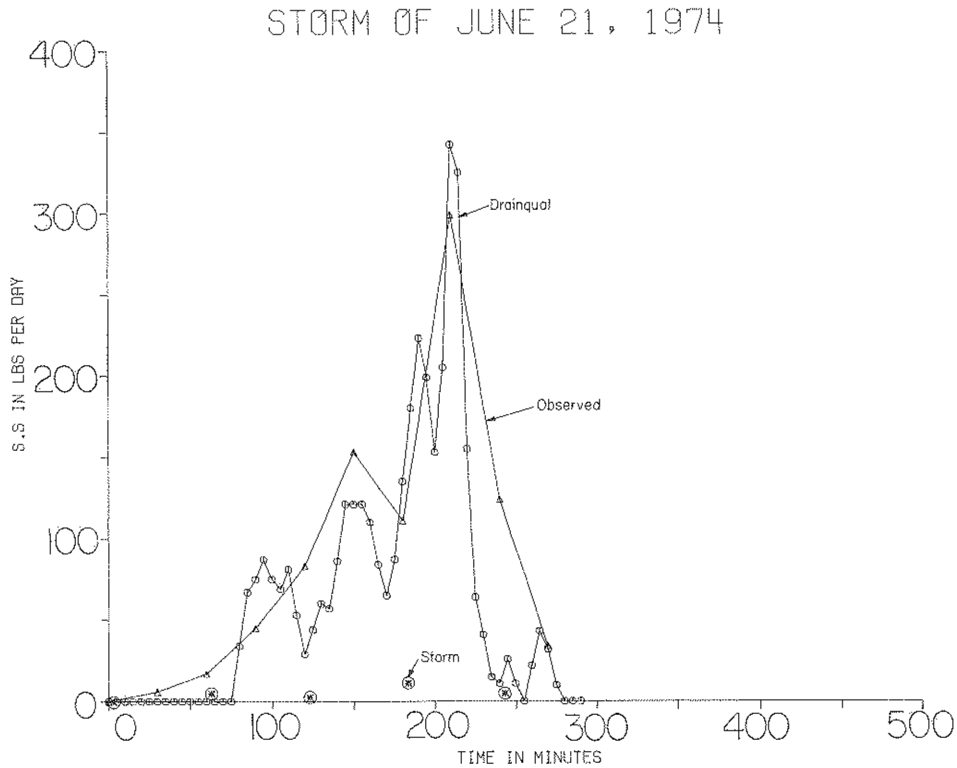


Figure 5.2 continued



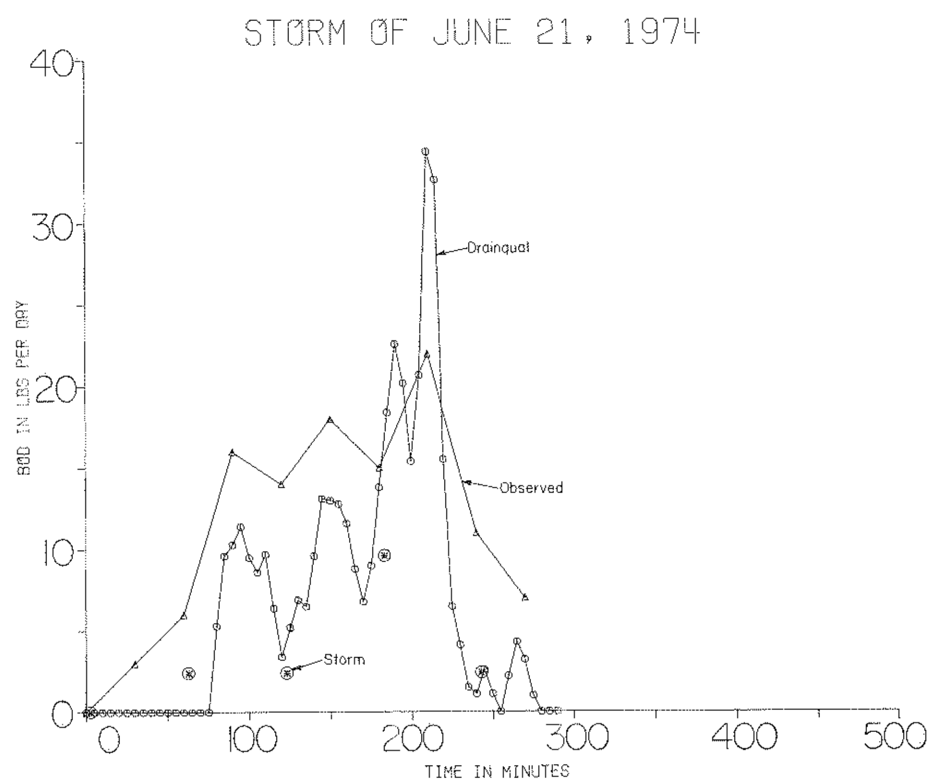
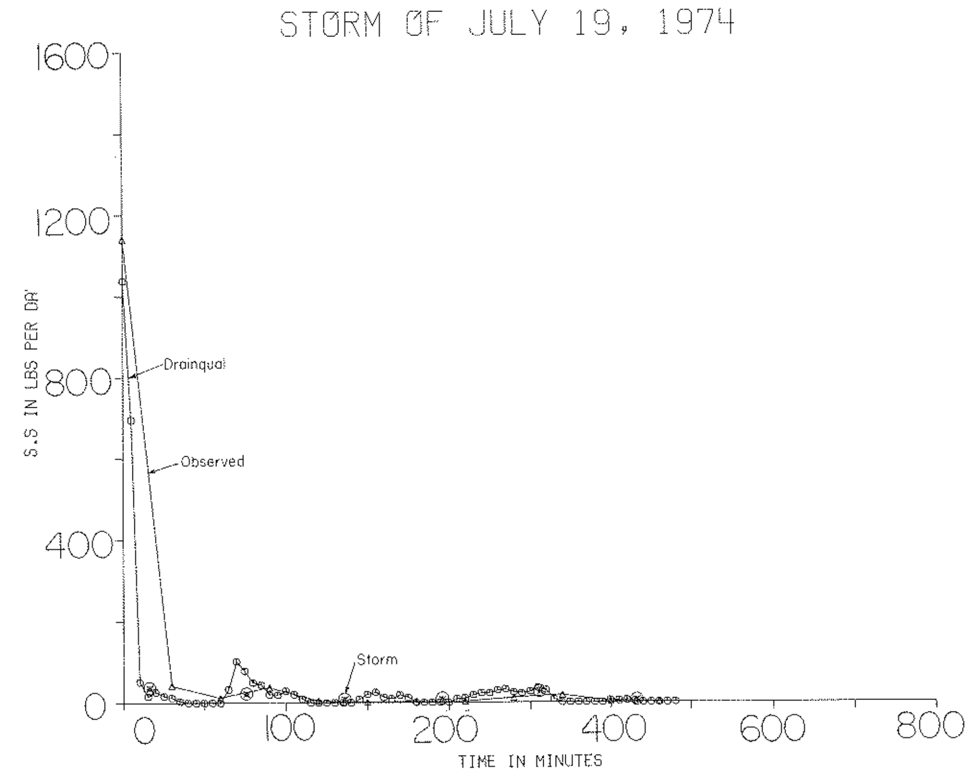


Figure 5.3 Observed and Calculated Pollutographs by the DRAINQUAL Model



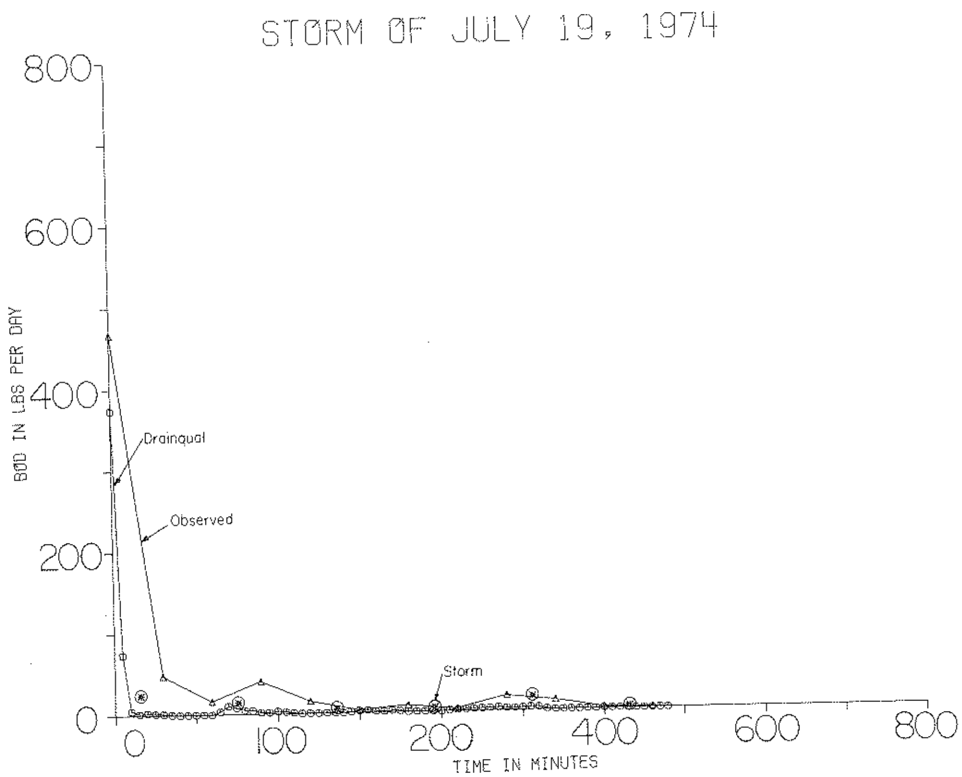
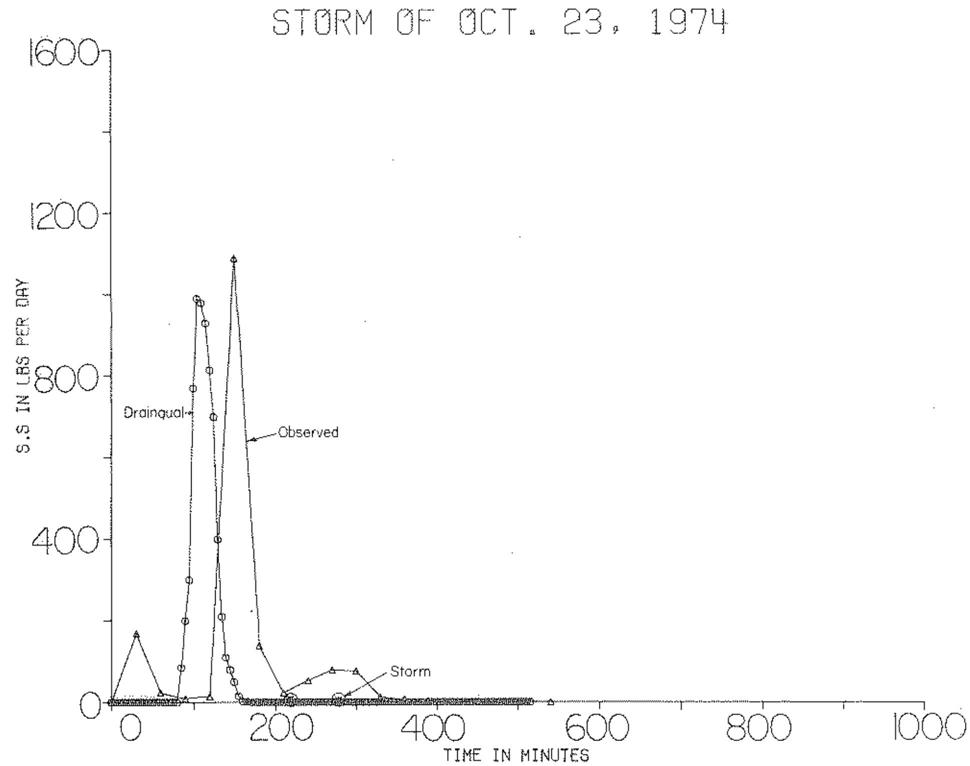


Figure 5.3 continued



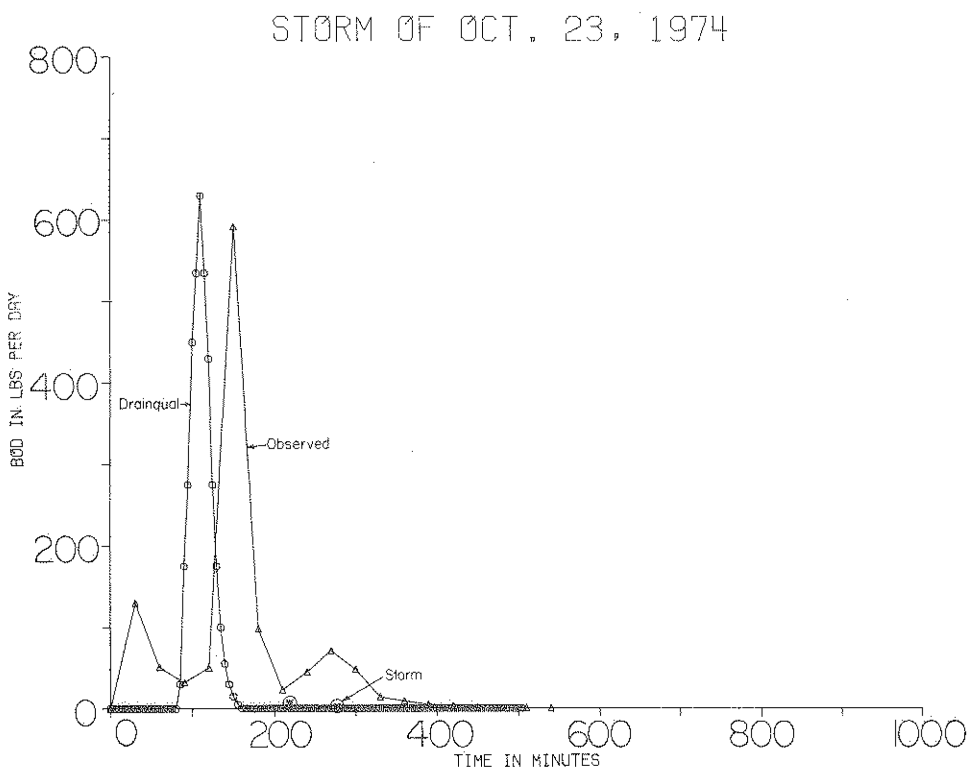


Figure 5.3 continued

CHAPTER 6

CALIBRATION AND SENSITIVITY ANALYSIS OF THE CONTINUOUS RUNOFF SIMULATION MODEL STORM

6.1 INTRODUCTION

This portion of the study relates to the hourly continuous runoff simulation part of the model STORM (Storage, Treatment, Overflow, Runoff Model) developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers. As this model is used extensively in this research it was deemed necessary to do a detailed calibration and a sensitivity analysis of the hydrology portion of the model. The upper Ross-Ade watershed in West Lafayette was used for this purpose. The water quality aspects of the model had previously been calibrated by Hartman*.

The objectives of this section were the determination of the sensitive parameters of the hydrologic simulation of the model STORM and the careful calibration of the model.

Hartman, D. W., "The Monitoring and Prediction of Storm Water Quality from Watershed in West Lafayette, Indiana," M.S.C.E. Thesis, Purdue Univ. December 1975, J. M. Bell, Major Professor.

6.2 SENSITIVITY ANALYSIS

The total amount of runoff and the hourly runoff hydrograph at a given point in a rural and/or urban watershed are calculated by the model for each storm event. Different procedures are used for rural, urban areas and semi-urban areas. This study is limited to the rainfall-runoff function of STORM. The options involving snowmelt (unavailable data), diversion, storage and treatment were not considered.

In rural areas the model utilizes the Soil Conservation Service procedure, which requires among other quantities, the maximum soil moisture capacity and the maximum soil percolation rate. In urban areas the runoff is estimated in terms of net rainfall (rainfall minus depression storage) and a composite runoff coefficient. The runoff coefficient for the pervious surfaces and for the impervious surfaces are weighed proportionally to the fractions of the watershed that are pervious and impervious to form the composite runoff coefficient. In semi-urban areas the model combines both methods.

The Ross-Ade Upper Watershed in West Lafayette, Indiana, used for the calibration, has an area of 29 acres of which 11 acres are impervious. Hourly rainfall data in 1/100 inches from April 20, 1970, through November 29, 1971, were used. These included 225 days of record and 58 rainy days. Measured runoffs were also available for the same period.

Theoretical expressions were derived for the relative error in the composite runoff coefficient. Figure 1 illustrates the absolute value of the relative error in the composite runoff coefficient due to errors in pervious and impervious runoff coefficients for an area equally divided between the four following land uses: commercial, industrial, multiple family housing and single family housing. Figure 2 shows the relative error in the runoff due to relative errors in the rainfall and in the composite runoff coefficient. From Figure 2 it is seen that there is an infinite number of possible sets of values of the rainfall and of the composite runoff coefficient which yield zero error, but only a few have the correct physical significance and are acceptable. The analysis shows that the relative error in the surface runoff coefficient is a decisive one. The model completes the number of events for which the rainfall exceeds the maximum depression storage. The observed and computed total amounts of runoff by events for the urban area was adequately fitted by a Gamma distribution as shown in Figure 3.

Analyzing the watershed as a semi-urban area, the pervious area is treated by the SCS method. In this method the rainfall, the initial abstraction and the soil moisture storage are coupled in a nonlinear way to determine the runoff. The behaviour of the total amount of runoff is thus analyzed as a function of each parameter considered sequentially. As shown in Figure 4, the maximum soil moisture retention practically determines the amount of water available for runoff. The starting soil moisture retention, however, relates only to the first step in the calculation and is seen to have no measurable effect on the amount of yearly runoff.

Similarly, Figure 5 shows that the starting value of the initial abstraction has no measurable influence on the total yearly runoff, whereas the effect of the maximum value is a decisive one. The observed and computed total runoff by event for the semi-urban area were also fitted by a Gamma distribution, as shown in Figure 6, however the fit is not as good as for the urban area analyzed by the composite runoff coefficient method.

6.3 PUBLICATIONS

For further details on the calibration and sensitivity analysis of the hydrologic part of the model STORM the reader is referred to the following publications.

PWRRC Tech. Rept. 103, "Calibration and Sensitivity Analysis of the Continuous Runoff Simulation model "STORM"," by J. L. Sautier and J. W. Delleur, May 1978.

J. L. Sautier and J. W. Delleur, "Calibration and Sensitivity Analysis of the Continuous Runoff Simulation Model STORM," Proceedings, Intl. Symp. on Urban Storm Water Management, Univ. of Kentucky, July 1978, pp. 73-79.

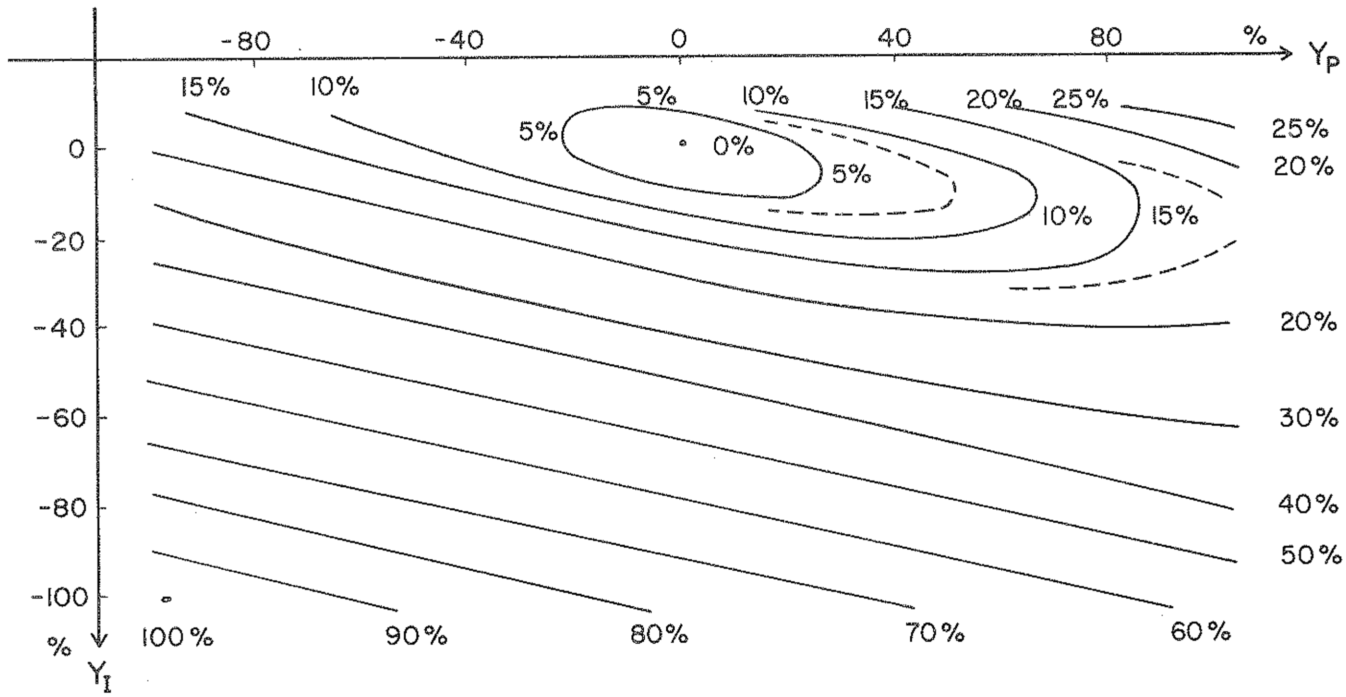


Figure 6.1 Average of the Absolute Values of the Relative Errors Z_{PI} in the Composite Runoff Coefficient Due to Errors Y_P and Y_I in the Runoff Coefficient for the Pervious and Impervious Surfaces, Respectively, for an Area with 4 Land Uses Equally Distributed

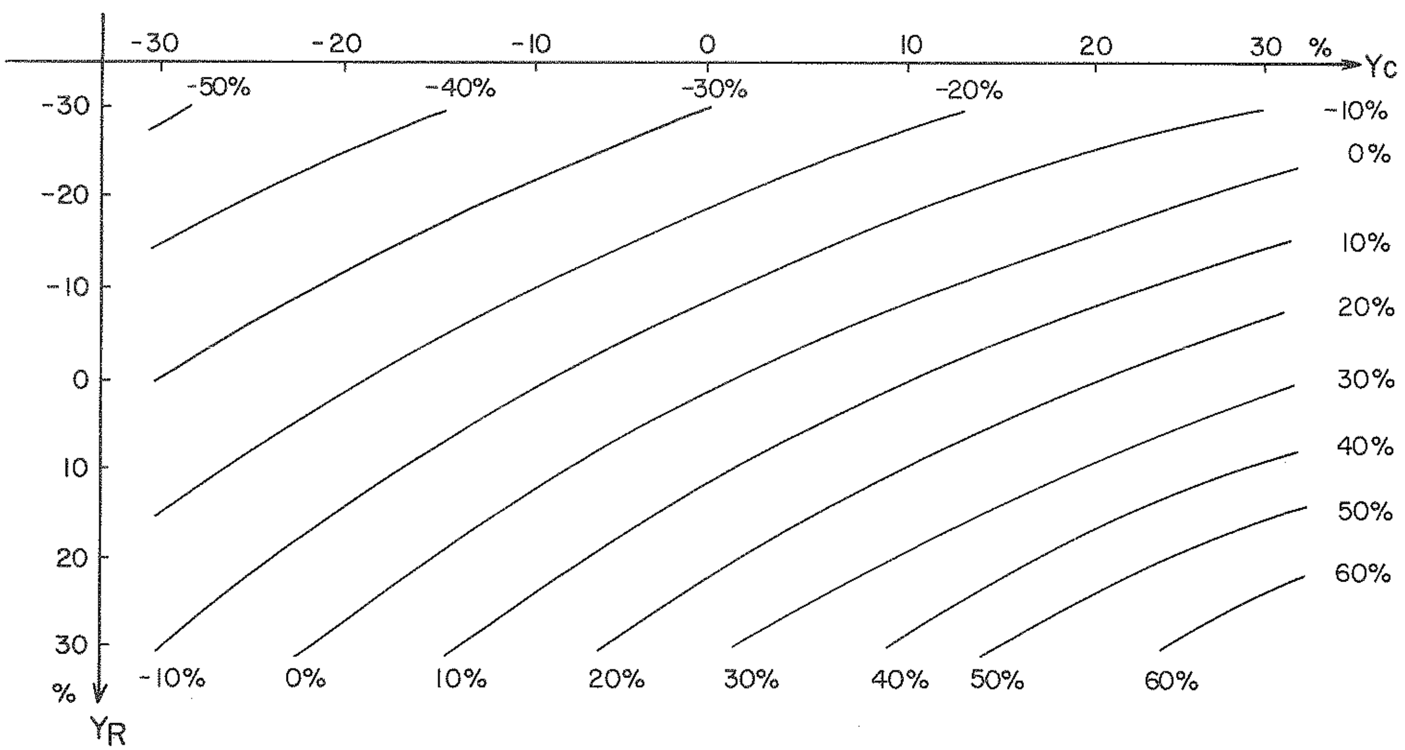


Figure 6.2 Relative Error Z_{RC} in the Runoff Due to Relative Errors Y_R in the Rainfall and Y_C in the Composite Runoff Coefficient

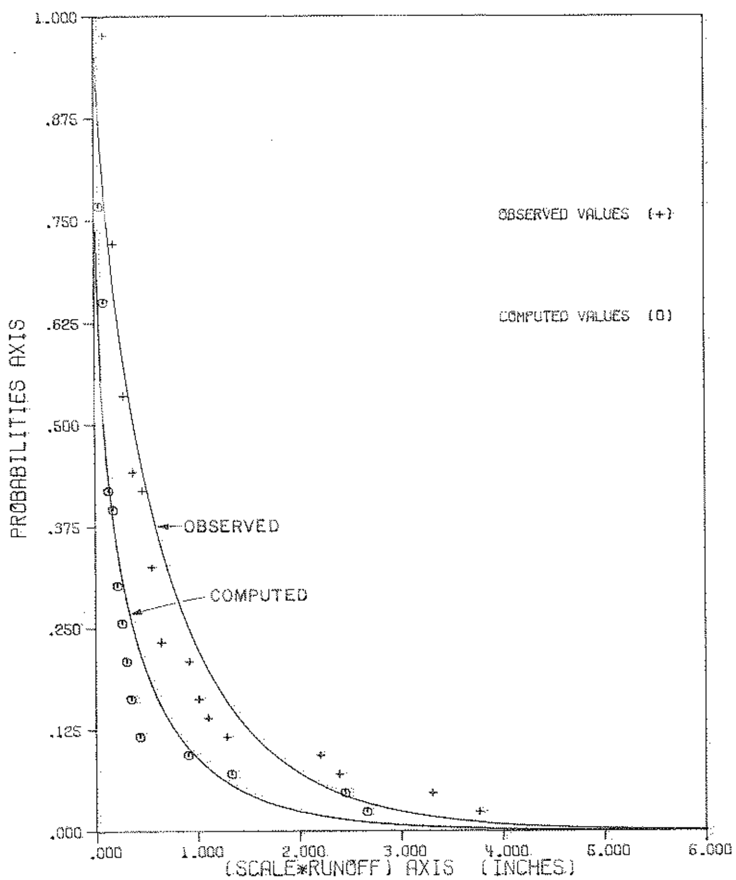


Figure 6.3 Observed and Computed Total Amounts of Runoff by Event for Urban Area

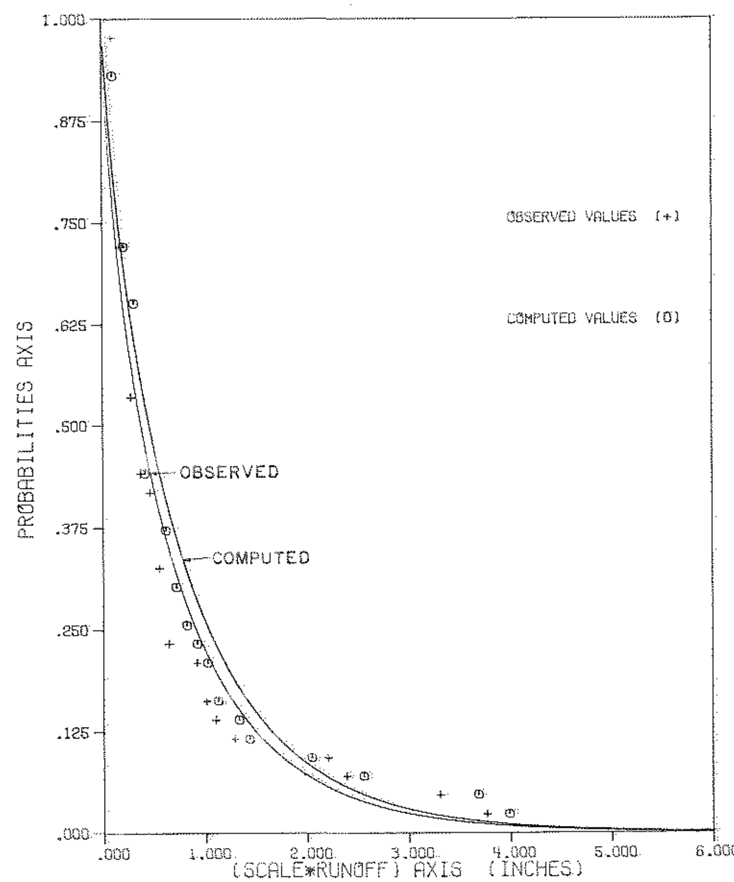


Figure 6.6 Observed and Computed Total Runoff by Event for Semi-Urban Area

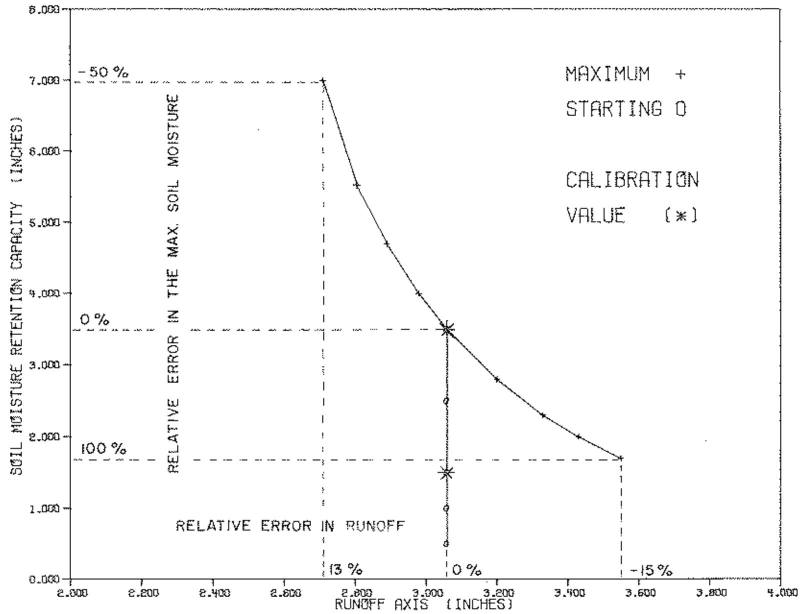


Figure 6.4 Variation in Total Runoff Due to Variations in the Maximum and Starting Values of the Soil Moisture Retention Capacity

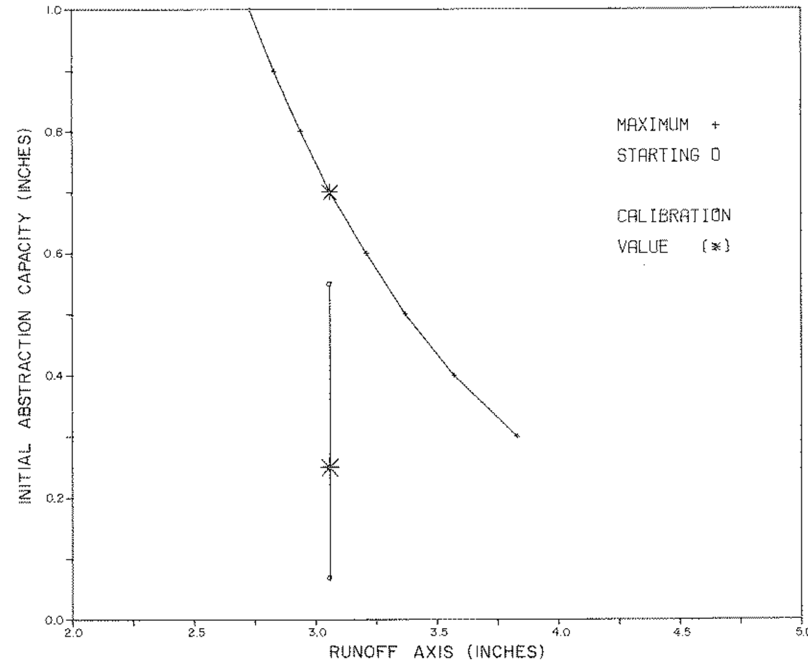


Figure 6.5 Variation in Total Runoff Due to Variations in Maximum and Starting Values of the Initial Abstraction Capacity

Chapter 7

A Statistical and Stochastic Analyses of Synthetically Generated Urban Storm Drainage Quantity and Quality Data

7.1 INTRODUCTION

Rainfall data are usually available for fairly long periods. In such cases the simulation program "STORM" can be used for the continuous simulation of quantity and quality of storm water runoff. There is much more information that can be extracted from this simulation than is generated by the program. The programs STORM and ILLUDAS can be conveniently combined for economic analyses.

A) Objectives

As a result the following objectives of this portion of the study were set.

1. To extract as much statistical information as possible from the continuous simulation generated by "STORM" for a long rainfall data series.

2. To explore the possibilities of manipulating the generated data to construct series of quantity and quality data of different time intervals leading to different additional statistical, regression, frequency and time series analyses that might be useful in storm drainage planning and in the generation of further synthetic data.

3. To develop a simple procedure for estimating the quantities of rainfall, runoff, suspended solids and BOD given a recurrence interval and a specified duration of even for a particular combination of storage and treatment rate.

4. To explore the possibility of using STORM to supplement data required for economic analysis in conjunction with ILLUDAS.

7.2 THE DATA

The hourly rainfall data for the station West Lafayette 6NW for the period 1953-1974 was used as input to the program STORM applied to the Upper Ross-Ade Watershed, a single family housing area in West Lafayette. Zero treatment rate and zero storage capacity was assumed. The 'events' generated by STORM correspond to the case when the storage is used. In this case the 'events' correspond to runoff-producing rainfalls. The other calibration parameters were obtained from references 1 and 2. The output of STORM was stored on magnetic tape from which hourly, daily, monthly and yearly series of rainfall events, runoff, suspended solids and BOD may be constructed.

7.3 STATISTICAL ANALYSIS

A total of 1826 events occurred during the entire period of record. Of these 730 are two-hour events, the most frequent ones, and 90% of the events had durations equal to or less than 7 hours. The means, standard deviations, skewnesses, coefficients of variation and lag one correlation coefficients were obtained for yearly and monthly rain, runoff, suspended solids and BOD. The coefficients of variation of rainfall were found to be uniformly small for all months (from 0.51 to 0.97) and those of suspended solids are relatively high (0.75 to 1.72). The months of June and October show the maximum variability for all quantities.

7.4 REGRESSION ANALYSIS

Linear regression models were developed to predict runoff quality parameters. Using observed data for 19 storms the total and peak suspended solids were found to be significantly correlated with the peak runoff, but the total and peak BOD did not correlate significantly with the total rain rainfall, maximum rainfall intensity, the antecedent dry period and the peak flow.

Due to the scarcity of observations of runoff quality data, further regression analyses were performed on the synthetic data generated by STORM. Taking the rainfall in inches (X_1) and the duration in hours (X_2) as independent variables and the suspended solids in pounds (Y_1) and the BOD in pounds (Y_2) as dependent variables, global and yearly correlations were obtained. The global correlations are

$$Y_1 = 60.79X_1 - 1.65X_2 - 5.244 \quad (\text{adj. } R^2 = o.4264)$$

$$Y_2 = 9.08X_1 - 0.07X_2 - 0.66 \quad (\text{adj. } R^2 = 0.577).$$

The year-wise regressions for suspended solids show a variation of the adjusted R^2 from 0.412 to 0.887 and for the BOD from 0.575 to 0.8962, indicating that the regressions are better in certain years than in others.

Regressions were also developed using the duration as a parameter varying from 1 to 6 hours in steps of one hour. The one-hour relationships are given as an example:

$$Y_1 = -6.889 + 62.385X_1 \quad (\text{adj. } R^2 = 0.9259)$$

$$Y_2 = -0.469 + 6.921X_1 \quad (\text{adj. } R^2 = 0.926)$$

The adjusted R^2 values varied from 0.9259 to 0.409 for suspended solids and from 0.926 to 0.5032 for BOD. In general, the adjusted R^2 values for those relationships using duration as a parameter are better than those of the global relationships.

7.5 FREQUENCY ANALYSIS

In the traditional "design storm" approach for the planning of drainage systems the frequency of occurrence of storms of various durations and intensities is considered without regard to the system and its response characteristics. A better approach consists in using the 'events' defined by STORM since they represent the effect of rainfall in relation to the storage capacity and treatment rate considered for the system. The event approach indicates how often the system is loaded to a certain level. The specific calculations performed correspond to the runoff-producing rainfalls. The same calculations could be repeated for other values of the treatment rate and storage capacity.

Annual extreme value and partial duration analsis were performed for rainfall, runoff, suspended solids and BOD. The 21 extreme value data for all quantities plotted as straight lines on Gumbel extreme value probability paper. The quantities, X, corresponding to a given return period T can be computed from the relation

$$X = u - \frac{1}{\alpha}\,\ell n[\ell n\ T - \ell n(T-1)]$$

with the following values of the parameters

	Rain	Runoff	Suspended Solids	BOD
u	2.2125	0.6044	106.4622	18.8317
$1/\alpha$	0.6717	0.3307	219.6256	23.4408

For the calculation of the suspended solids and BOD for a given rainfall duration and return period, it is recommended to use the Gumbel extreme value relationship to obtain the total amount of rain and the regression equations with duration as a parameter to obtain the expected suspended solids and BOD.

7.6 TIME SERIES ANALYSIS

Predictive models of the time series type were investigated making use of the observed monthly rainfalls and simulated monthly runoffs, suspended solids and BOD's. Both raw series and cyclicly standardized series were used. Cyclic standardization is achieved by the equation

$$Y_{p,t} = \frac{X_{p,t} - \overline{X}_t}{S_t}$$

in which $Y_{p,t}$ is the stochastic component of the series $X_{p,t}$ at month t of year p, $\overline{X}_t$ is the mean of the X values for the t-th month and S_t is the standard deviation for the t-th month. $Y_{p,t}$ is approximately standardized and stationary in the mean and variance.

The spectra show the significant yearly periodicity. The correlograms, in general, exhibit a significant lag one serial correlation coefficient. The transfer functions from monthly rainfall to monthly runoff, suspended soilds and BOD obtained by cross-spectral analysis decay quickly since the time step is one month. The transfer functions presuposing an autoregressive-moving average (ARMA) model were obtained for different pairs. They could be useful for the synthetic generation of one series such as suspended solids or BOD from an observed series such as rainfall. In the particular application tested the moments were not preserved.

It was found more practical to fit ARMA models to each individual series separately. The ARMA (1,1) model

$$X_t = \phi_1 X_{t-1} + \theta_0 + \theta_1 a_{t-1} + a_t$$

emerged as the best model, where X_t is the process variable cyclically standarized at time t, a_t is a random noise of zero mean and of variance σ_a^2. The model parameters are as follows for the monthly series:

	θ_0	ϕ_1	θ_1	σ_a^2
	-1.424×10^{-4}	-0.197	-0.2289	0.9969
Runoff	1.98×10^{-4}	-0.664	-0.755	0.9896
Suspended Solids	1.064×10^{-4}	0.6649	0.591	0.9861
BOD	7.21×10^{-6}	0.8182	0.749	0.9838

7.7 COST ANALYSIS AND STORM WATER MANAGEMENT

Alternative storm drainage plans must be analyzed in terms of the reliability of the system performance and of economic considerations. Simulation is an effective means of analyzing alternate control strategies. The frequency of allowable overflows in the receiving water body must be based on the quantity and quality of the untreated storm water. The evaluation of the cost of the system requires the estimation of the cost of the conveyance system (channels and sewers) the number and locations of the detention basins and the capacity of the treatment plants. Since the program STORM does not have the capability of channel and conduit routing and lumps the storage capacity over the basin, the program ILLUDAS may be used for the computations of the conveyance system and for evaluating the effect of alternative storage sizes and locations.

The economic analysis was performed for a 1912 acre watershed located in the Northern portion of West Lafayette, Indiana. The results are based on the simulation run of STORM for 22 years of rainfall data at the station West Lafayette 6NW. Four treatment rates were selected: 0.06, 0.04, 0.02 and 0.01 inches/hour corresponding to 75, 50, 25 and 12.5 myd and four storage capacities of 0.28, 0.139, 0.07 and 0.035 inches over the basin. These were analyzed in several combinations. The number of overflows and the overflow volumes were found to be sensitive to the treatment rate and the storage capacity. For example, at a treatment rate of 0.01 in/hr the average overflow volume decreases from 1.0 to 0.3 inches for an increase in storage of 0.2 inches. Whereas at a 0.06 in/hr treatment rate, the decrease in overflow volume is only 0.3 inches for the same increase in storage. A similar sensitivity is observed in the case of the average number of overflows per year. Figures 7.1 to 7.3 show the average number of overflows, the average overflow volumes of storm water, the average overflow of suspended solids and of BOD, all per year year, as a function of the storage capacity with the treatment rate as parameter.

7.8 CONCLUSIONS

1. For planning purposes it is more meaningful to analyze storm events in the context of the drainage system characteristics.

2. A continuous simulation of runoff quantity and quality is essential to this analysis.

3. Statistical analyses of synthetic data may be necessary where there is insufficient information on runoff quality.

4. A simple procedure involving frequency and regression analyses was developed for estimating quantities of rainfall, runoff, suspended solids and BOD of events, given the recurrence interval and the duration of the rainfall for a particular combination of storage capacity and treatment rate.

5. The models STORM and ILLUDAS can be used together advantageously for obtaining the necessary data for an economic analysis. While STORM can give the combinations of storage and treatment rates for specific overflow requirements, ILLUDAS can provide complementary information on the drainage network for various alternate sizes and locations of the storage.

7.9 PUBLICATIONS

For further details on the statistical and stochastic analysis the reader is referred to:

PWRRC Tech. Rept. 108, "A Statistical and Stochastic Analyses of Synthetically Generated Urban Storm Drainage Quantity and Quality Data," by G. Padmanabhan and J. W. Delleur, July 1978.

7.10 REFERENCES

1. Hartman, D. W., "The Monitoring and Prediction of Storm Water Runoff Quality from Watersheds in West Lafayette, Indiana," M.S. Thesis presented to Purdue University, December 1975.

2. Sautier, Jean L., and J. W. Delleur, "Calibration and Sensitivity Analysis of Continuous Runoff Simulation Model 'STORM'," Water Resources Research Center, Purdue University, West Lafayette, Indiana, Tech. Rept. 103, May 1978.

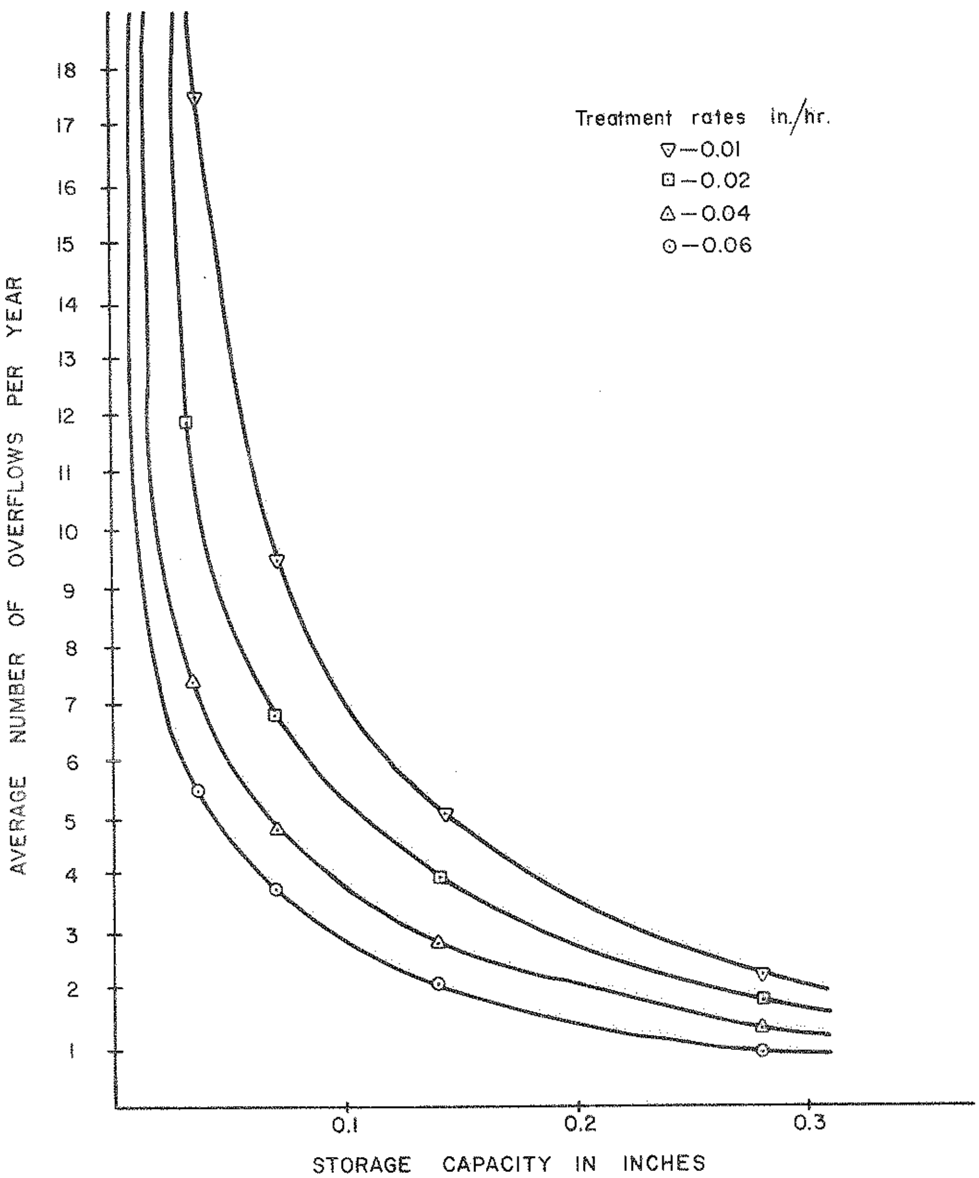


Figure 7.1 Average Number of Overflows

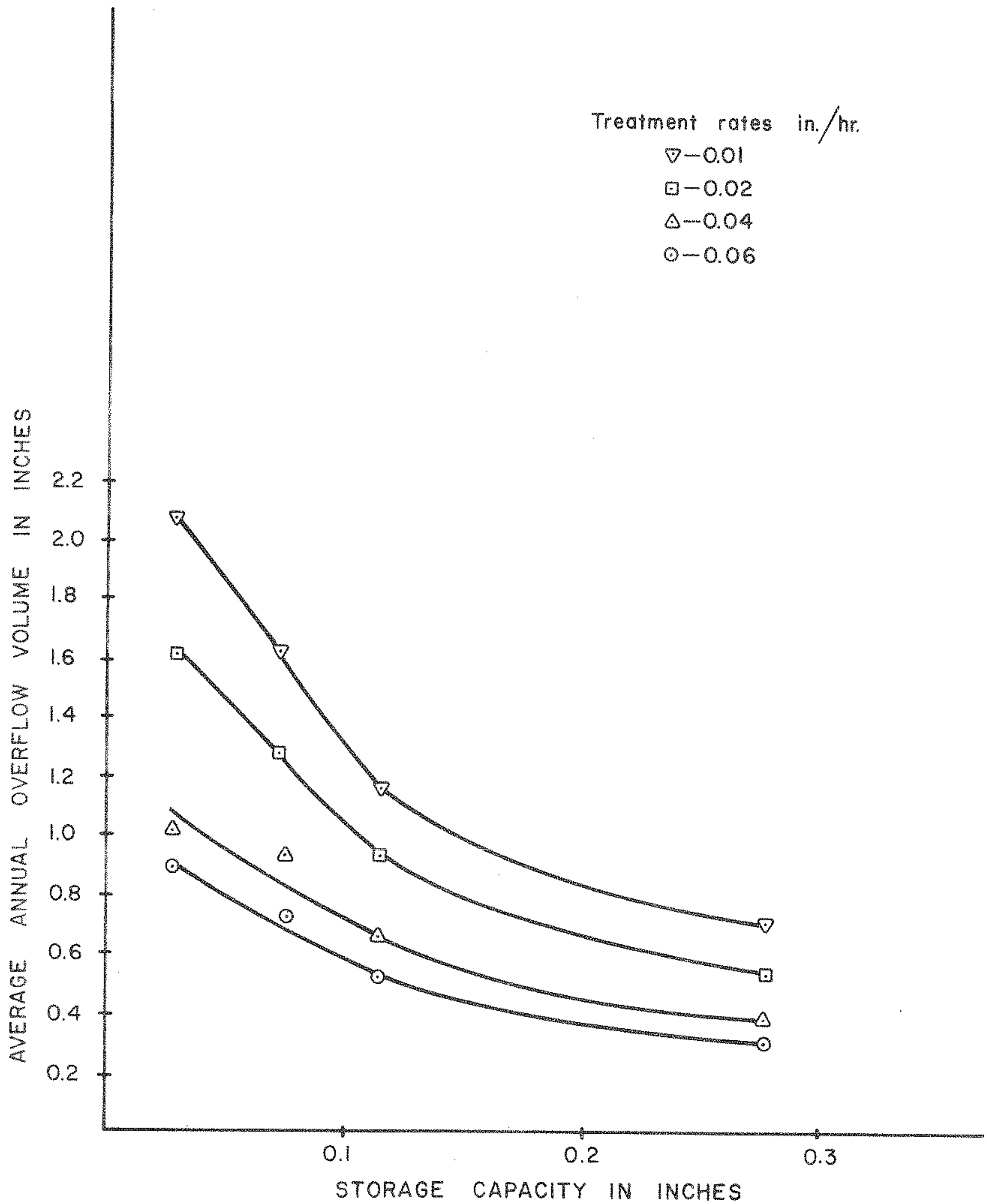


Figure 7.2 Average Overflow Volume per Year

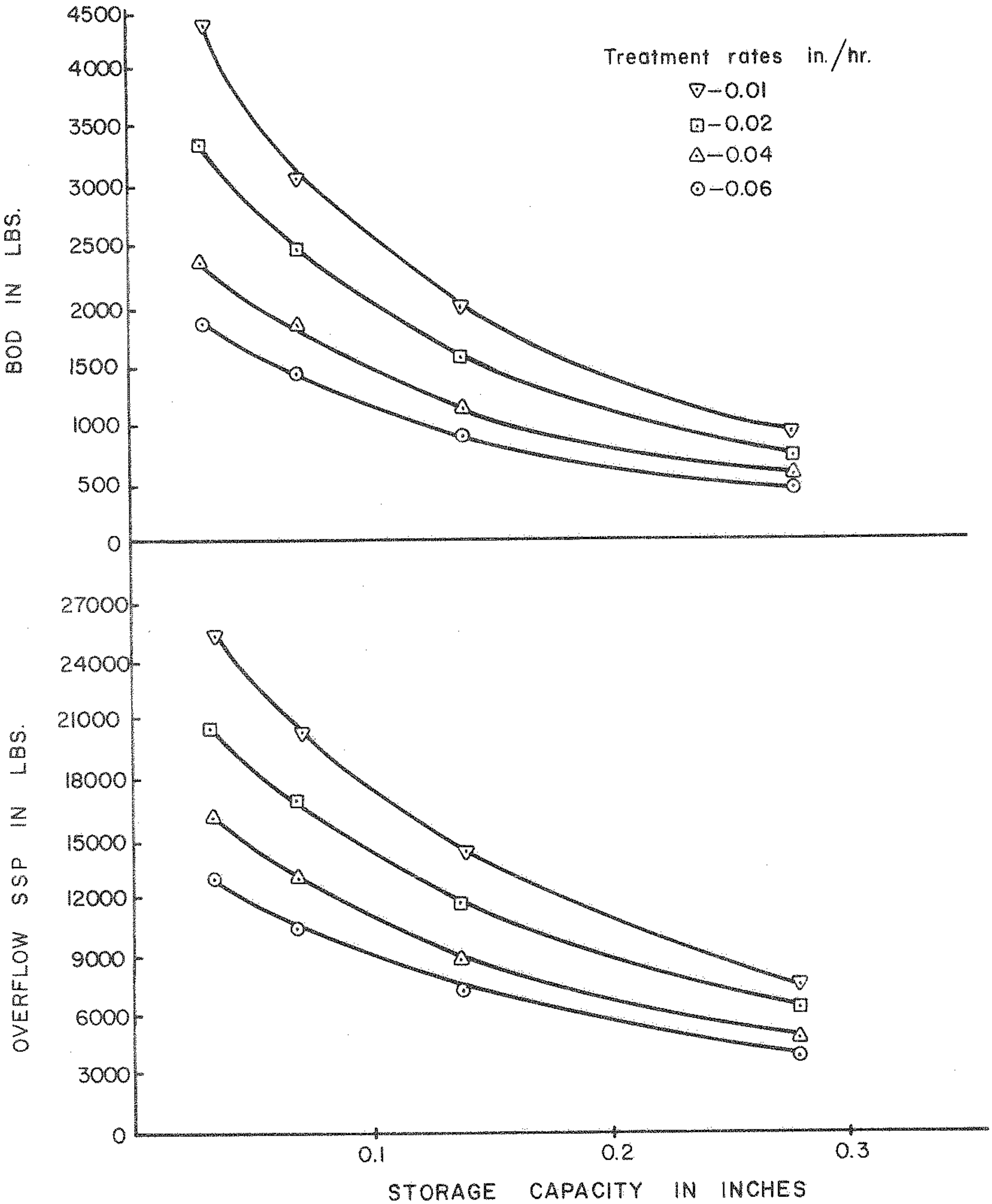


Figure 7.3 Average Suspended Solids and BOD per Year

CHAPTER 8

PROBABILISTIC APPROACH VS. STORMWATER MANAGEMENT MODEL STORM: A COMPARISON OF TWO METHODS OF ANALYSIS

8.1 INTRODUCTION

The statistical and stochastic analysis outlined in Chapter 7 incorporated all of the events and dry periods occurring in a period of 22 years. Such an analysis is obviously influenced by the extreme occurrences of stormwater events and dry periods. A probabilistic approach, however, utilizes only the "expected" events and dry periods, thus eliminating the extreme occurrences from the analysis. This chapter is a comparison of these two analytical approaches and provides an estimate of the amount of stormwater pollution which can be attributed to the extreme events. This information will be useful in developing a stormwater management system.

8.2 RAINFALL MASS CURVE

The Expected Rainfall Depth Curve (Fig. 8.1) was developed from rainfall data gathered during Phase I of this project at the Upper Ross-Ade Watershed in West Lafayette, Indiana. The depth and duration data at 10 minute intervals for a period of three years were obtained from Tech. Rept. No. 55*. The storms are divided into three types based on the maximum 10 minute rainfall occurring in the event. The three types are: trace (10 minute rainfall peaks less than 0.03"), moderate (between 0.03" and 0.09"), and peak (greater than 0.09"). Each storm type is divided into nine classes based on duration of the rainfall event, resulting in 27 sub-types of storms. The expected rainfall depth for the several given sub-types were obtained making use of regression relationships developed in Phase One*. The construction of the Expected Rainfall Depth Curve involves summing the rainfall subtypes weighted by their frequency of occurrence and their rainfall depth. It can be seen in Figure 8.1 that approximately 80% of the yearly rainfall depth is generated by storms of 1 inch or less total depth. A cumulative probability curve of the expected frequency of events is presented in Figure 8.2. The relationship between percentage of events and percent of the expected rainfall is expressed in the table below. The peak storms clearly possess the most depth per storm compared to the other types. Although trace storms account for about 40% of the rainfall events, they only contribute 15.4% of the rainfall.

Probabilistic Analysis and Simulation of the Short Time Increment Rainfall Process. Rao, A. R., and Chenchayya, B. T., Purdue Water Resources Research Center, Technical Report No. 55.

Storm Type	Percent of Events	Percent of Expected Rainfall	Ratio %Rainfall/% Events
Trace	40.40	15.40	0.38
Moderate	39.90	42.90	1.07
Peak	19.70	41.50	2.11

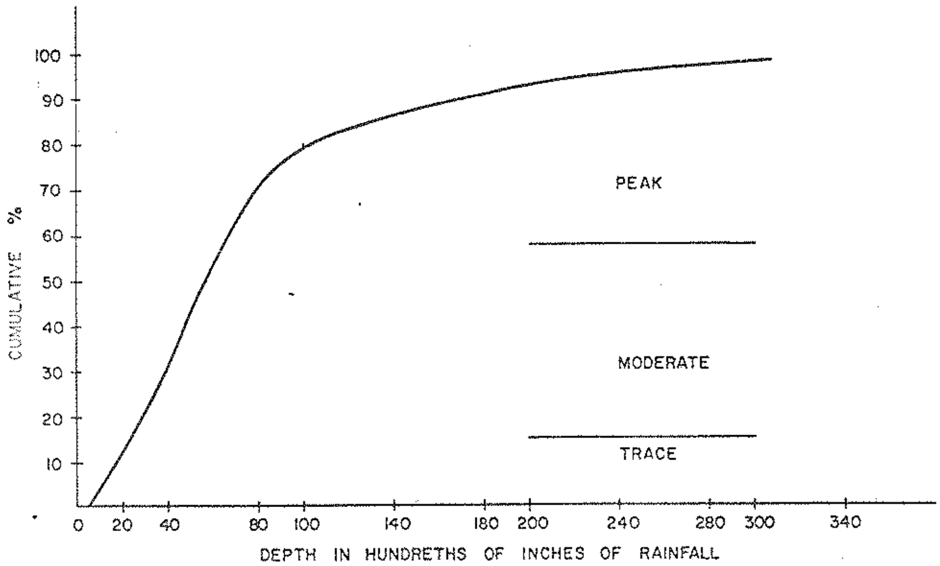
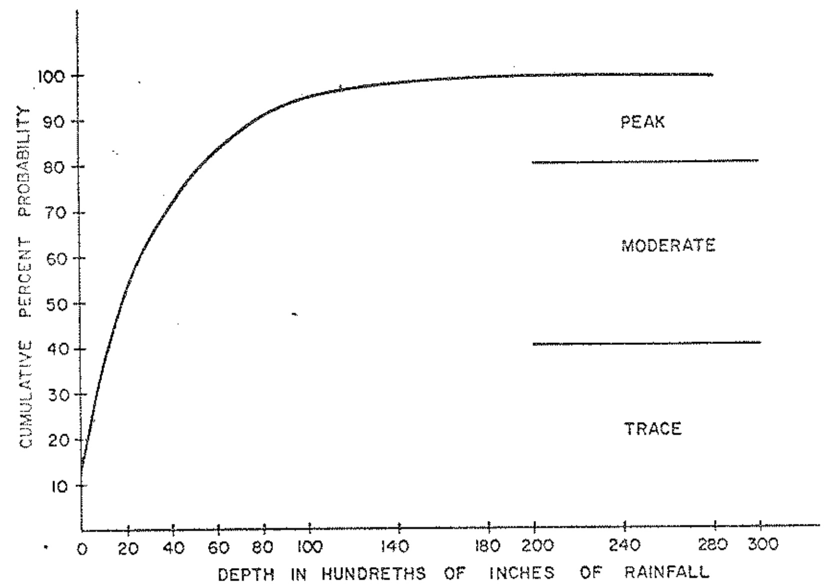


Figure 8.1 Expected Total Rainfall Depth Curve Cumulative % vs. Depth of Event

Figure 8.2 Expected Cumulative Rainfall Frequency Curve % of Events vs. Depth



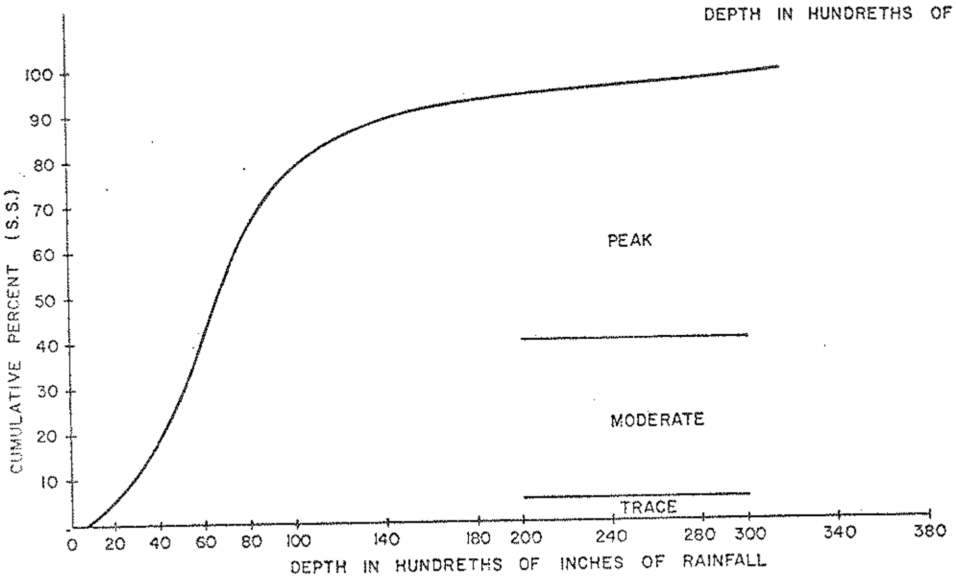


Figure 8.3 Expected Total Suspended Solids Mass Curve Cumulative % vs. Rainfall Depth

8.3 THE SUSPENDED SOLIDS MASS CURVE

The suspended solids mass curve, developed for the Upper Ross-Ade Watershed in West Lafayette area, is based on the following conditions:

1. The expected first quartile profile, developed by Chenchayya and Rao, Technical Report No. 55, is utilized as a standard hyetograph for the selected events used to construct the mass curve. First quartile storms are used because they produce the greatest amount of pollutants as compared to other quartile storms. First quartile storms are considered representative of the thunder shower and other intense storm types common to this area; and would provide a representative pollutant mass curve for the stormwater they produce.

2. A uniform set of conditions is used in the input into the program STORM for the analysis to insure unbiased pollutant loadings.

3. Because of the difficulty in simulating the BOD_5 in stormwater due to seasonal changes, fertilizer applications, and other uncontrolled and unaccounted for occurrences, suspended solids was chosen as the most representative pollution parameter.

The construction of the mass curve for suspended solids using the data generated by STORM is similar to that of the rainfall mass curve with the exception that the pounds of suspended solids per class-type event is used in place of the rainfall. The mass curve is illustrated in Figure 8.3.

8.4 COMPARISON OF THE RAINFALL AND S.S. MASS CURVES

A comparison of the rainfall and suspended solids mass curves is presented in Figure 8.4. The more conservative parameter may be estimated by plotting the percentiles for each for a given depth. From the graph it appears that rainfall is the more conservative estimator than suspended solids past the 80% level. There is a lag in the suspended solids mass curve due to the fact that very small events rarely produce any measurable runoff. This appears to be the most significant phenomenon that accounts for the suspended solids curve being the more conservative in the lower percentile range. However, as a first approximation, a linear relationship could be assumed between the cumulative percentage of rainfall and the cumulative percentage of suspended solids at least past the 80% level. This figure will be referred to as the "S" curve.

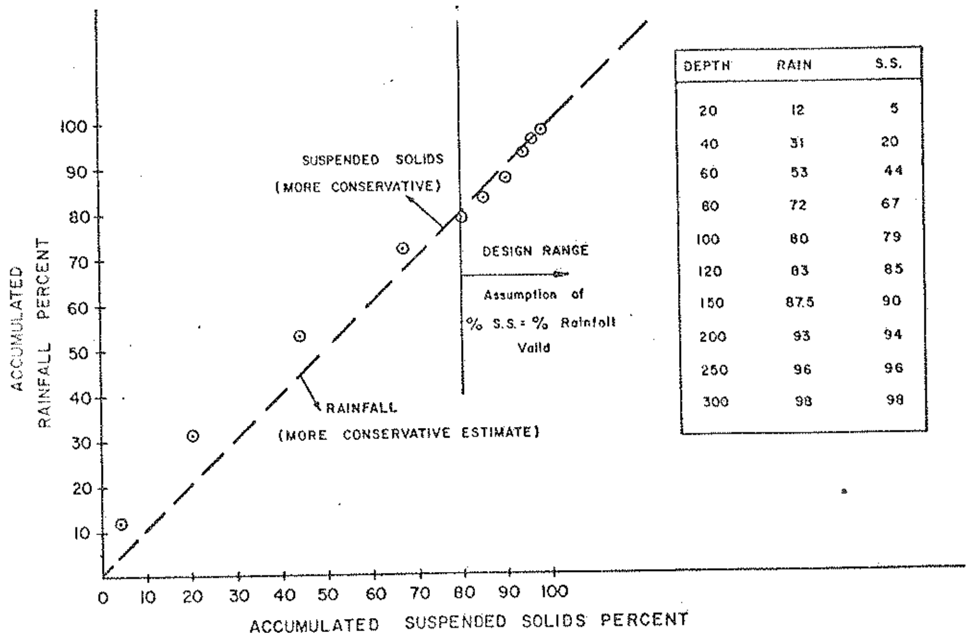
8.5 DEVELOPMENT OF THE EXPECTED STORAGE UTILIZATION CURVE

The expected storage utilization curve is constructed by first determining the percent of rainfall in excess of a given storage. By doing this for a series of storages one obtains the percent rainfall as a function of the storage depth. The percentage of pollutant remaining plotted vs. the storage depth is called the storage utilization curve and it is presented in Figure 8.5 for several treatment efficiencies. The curve illustrates the percentage of pollutant remaining in the storm runoff for a given storage depth and a given treatment efficiency. It can be seen that the change in percent pollutants remaining vs. change in depth is relatively small in the region where the rainfall mass curve is conservative estimate of the suspended solids mass curve. This region is also considered to be the design region for stormwater treatment, assuming one wants to remove a substantial amount of the pollutants.

To obtain an insight as to the percent of pollutants that will overflow (assuming the storage basin can be emptied before the next event occurs) in a given watershed in the area, an analysis using the rainfall mass curve would be sufficient. Also the expected runoff/rainfall ratio is necessary to convert inches of rainfall into inches of storage. This is applicable to any watershed for which the rainfall mass curve applies. The ratio can be obtained using the ARS curve number technique and STORM calculates the ratio to be 0.15 for the Upper Ross-Ade Watershed in West Lafayette.

8.6 THE EFFECTS OF STORAGE ON DIFFERENT QUARTILE STORMS

Rainfall patterns can be classified into types of storms, quartiles, designating the point of greatest intensity. Since the collection of stormwater commences at the beginning of runoff, the overflow pollutant load will be dependent upon the type of quartile storm involved.



DEPTH	RAIN	S.S.
20	12	5
40	31	20
60	53	44
80	72	67
100	80	79
120	83	85
150	87.5	90
200	93	94
250	96	96
300	98	98

Figure 8.4 Rainfall Mass Curve vs. Suspended Solids Mass Curve

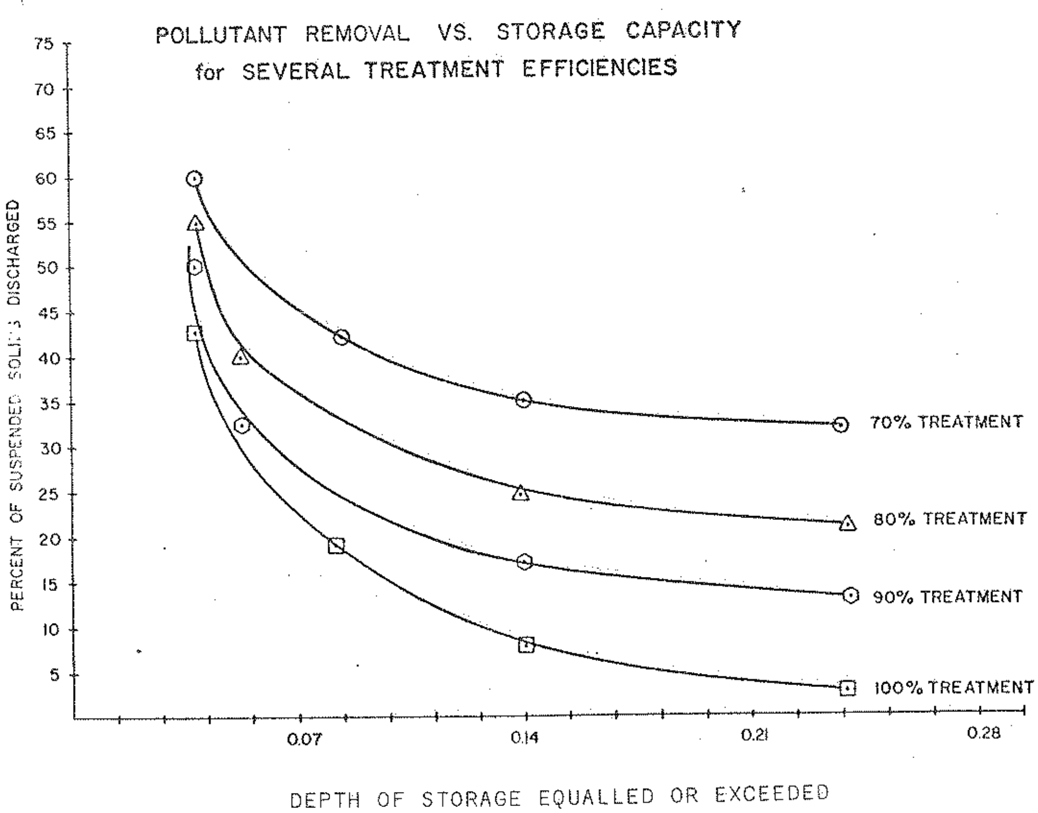


Figure 8.5 Storage Utilization Curve

The distribution on a percentage basis of the four quartile types for the Lafayette area is given below.

First Quartile - 32.8   Third Quartile - 5.5
Second Quartile - 32.3   Fourth Quartile - 19.5

By plotting the pounds of pollutants vs. the rainfall duration for the expected first quartile storms used to construct the S.S. mass curve, a comparison of trace, moderate and peak storms can be made (see Fig. 8.6). From the graph it is clear that the peak storms are much more severe in their pollutant loadings for a given duration than the other storms. Considering these peak storms are also the storms possessing the most intense rainfall; they are obviously the hardest of the three to treat by any method. Also the total pounds of pollutants that are washed off vs. depth of storm appears to approach a maximum value at large rainfall depths. This is expected since there is a finite amount of pollutants available due to previous washoff and street sweeping.

In order to assess the effectiveness of storage on the retention of peak storms an analysis of the various quartile peak storms is necessary. Profiles for the four quartile types were taken from Chenchayya and Rao, Technical Report No. 55, and the lbs. of suspended solids vs. rainfall duration for the four quartiles are shown in Figure 8.7. It is apparent from the graphs that the relationships between the different quartile storms are dynamic, i.e. there is no constant relationship as to the magnitude of pollutants discharged or % difference between the different storm types with respect to duration. The total pollutants from the second and third quartile storms are virtually the same for all durations. The peak storms dominate as expected, but with the highest percentage difference occurring in the middle range. This is probably due to the first order effect of pollutant washoff.

The next step in the analysis is to compare the cumulative percent pollutant discharge profile for the quartile storms at their respective % runoff, The profiles are presented in Figures 8.8 and 8.9 for rainfall durations of 350, 500, 650 and 800 minutes. Only the first three quartile types are used in conjunction with a 1:1 pollutant to runoff rates. There are two important observations in these profiles. The first is that the first three quartile storm types are progressively increasing their overall (%pollutant/%runoff) ratio in the first half of the storm. This phenomenon demonstrates the effect of storm intensity on the discharge of pollutants; i.e. generating the majority of the pollutants in the first half of the runoff volume. Remember the respective quartile storms have the same hyetograph, therefore only the depth and the corresponding intensity changes with duration. The second observation is that the rate of change of the phenomenon described above is different for each quartile type.

Making use of the % runoff-duration curves weighted by the total pounds generated by their respective storms the magnitude of the pollutant overflow is determined as shown in Figure 8.10. The results reveal the interactions of storage capacity and total pollutant load on each storm type. Although 1st quartile storms produce the most pollutants, they are the most receptive to storage retention, producing the lowest overflow loads. As seen from the graphs, the relationships between quartile types is not constant over the durations studied. In general, for the larger duration storms, greater than 50 units, the order of severity of pollutant loading is the inverse of the total pollutant loading. For the lower duration storms the 2nd quartile storage overflows are adequately estimated by the direct runoff-pollution assumption, the "S" curve, in this region. Also the "S" curve is a conservative estimate of pollutant overflow, for the larger duration events. Since the fourth quartile storms are closely related to the "S" curve, one is justified in using the "S" curve as a "worst case" design parameter and estimator, without being significantly overdesigned.

The use of the rainfall storage utilization curve for estimating the amount of storage required to provide a given level of treatment can be justified if the watershed experiences the first flush effect. It is recognized that this approach is an oversimplification of the rainfall-runoff-pollutant loads system. The proposition is that the expected relationships will be dominant over the long run.

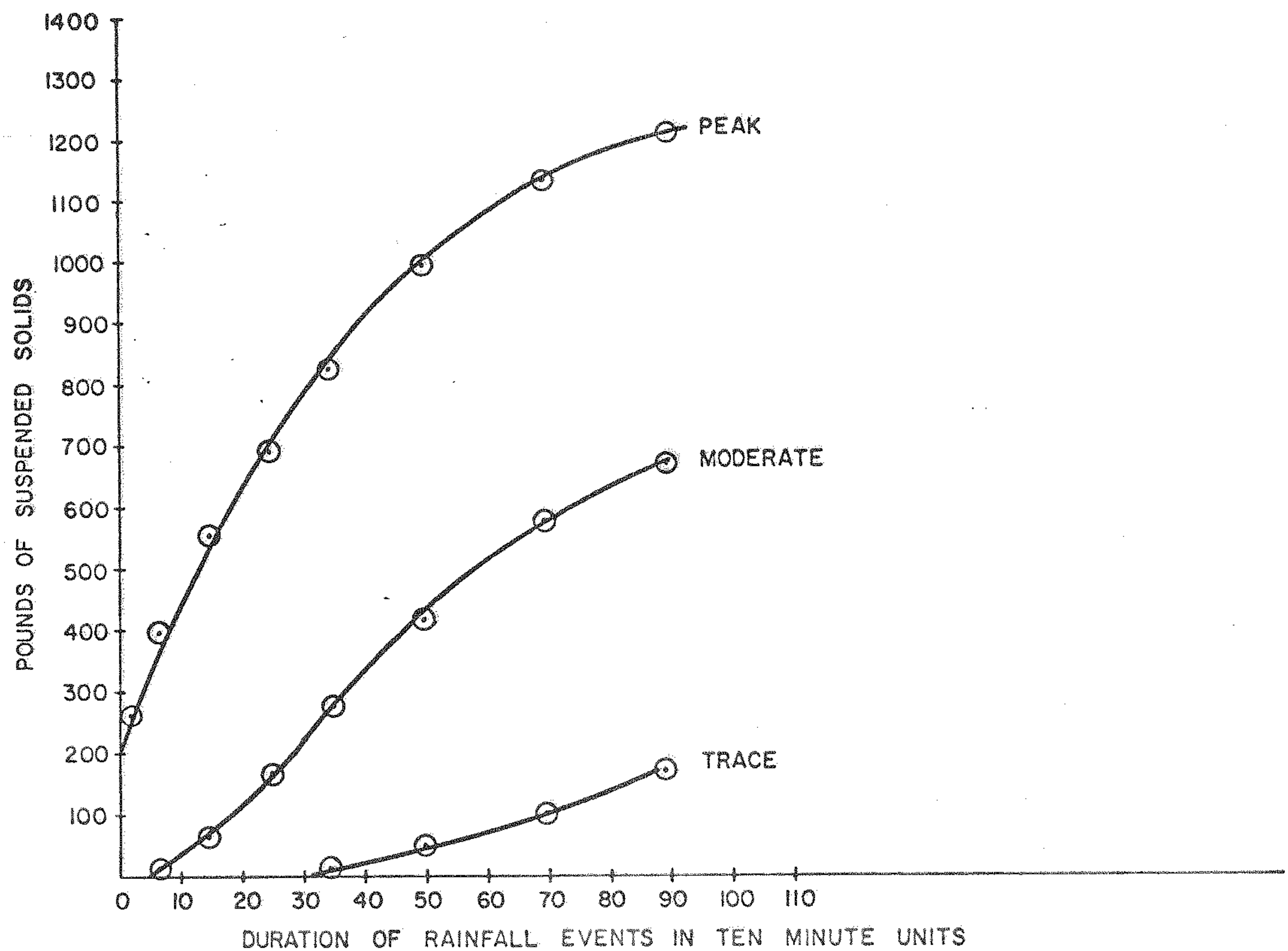


Figure 8.6 Pollutant Response to Rainfalls of Different Types for First Quartile Storms

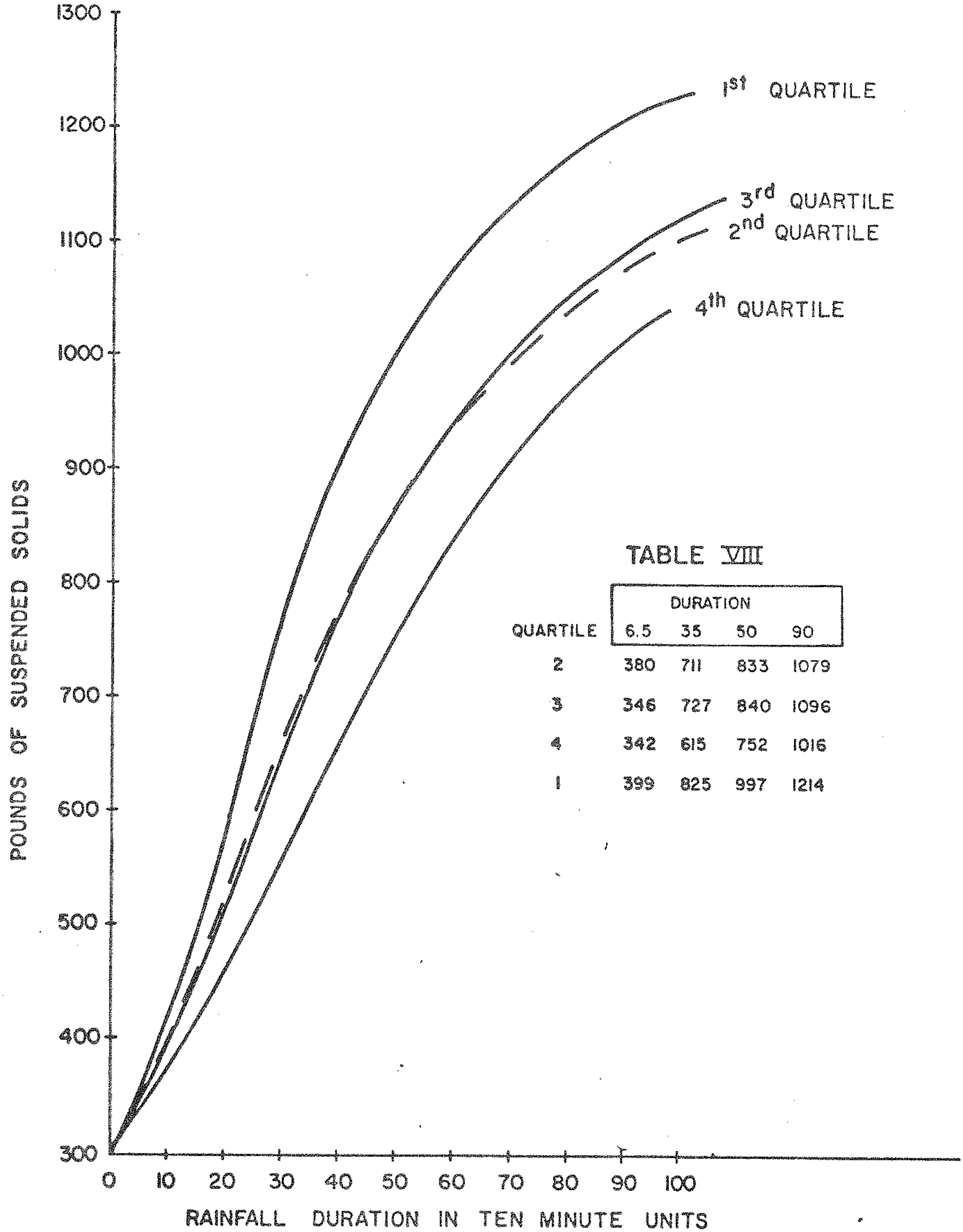


TABLE VIII

QUARTILE	DURATION 6.5	35	50	90
2	380	711	833	1079
3	346	727	840	1096
4	342	615	752	1016
1	399	825	997	1214

Figure 8.7 Pounds of Suspended Solids per Storm vs. Duration at Four Different Quartile Peak Storms

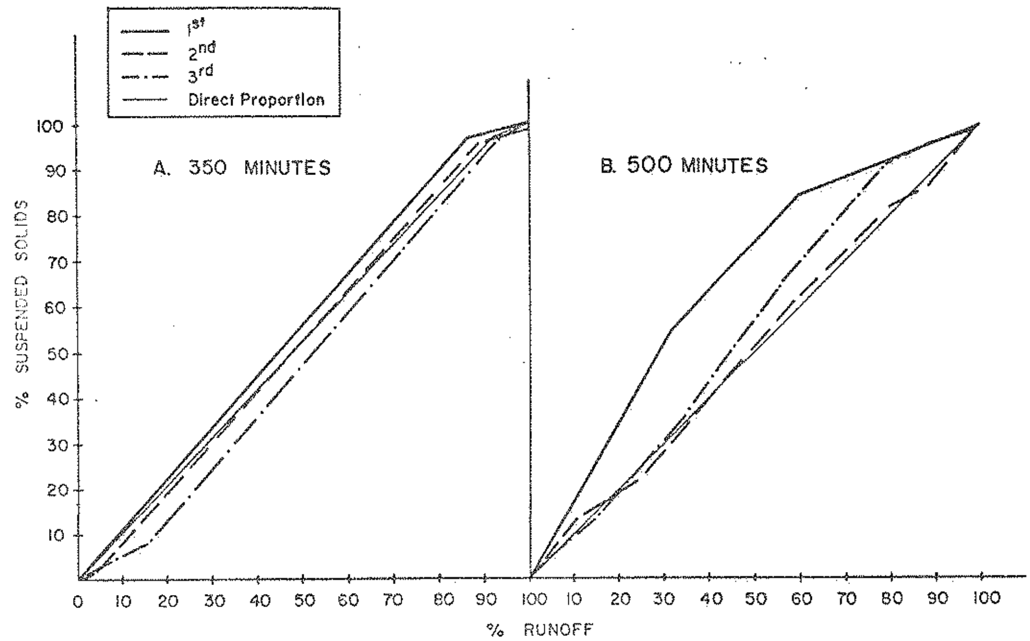


Figure 8.8 Pollutant Runoff Profiles for STORM

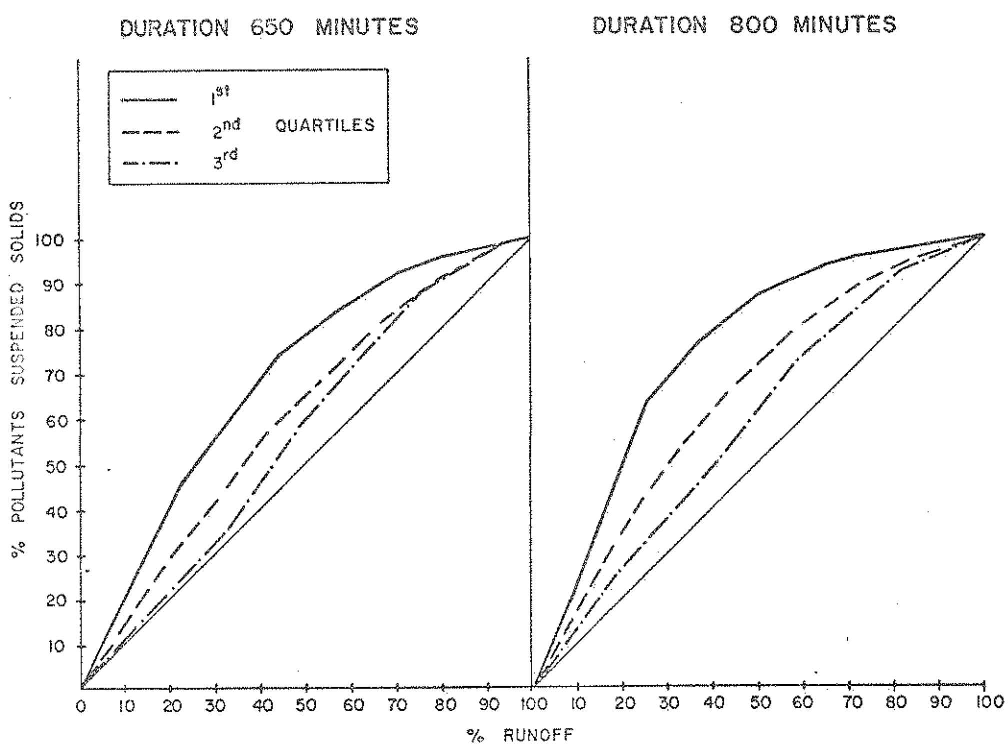


Figure 8.9 Pollutant Runoff Profiles for STORM

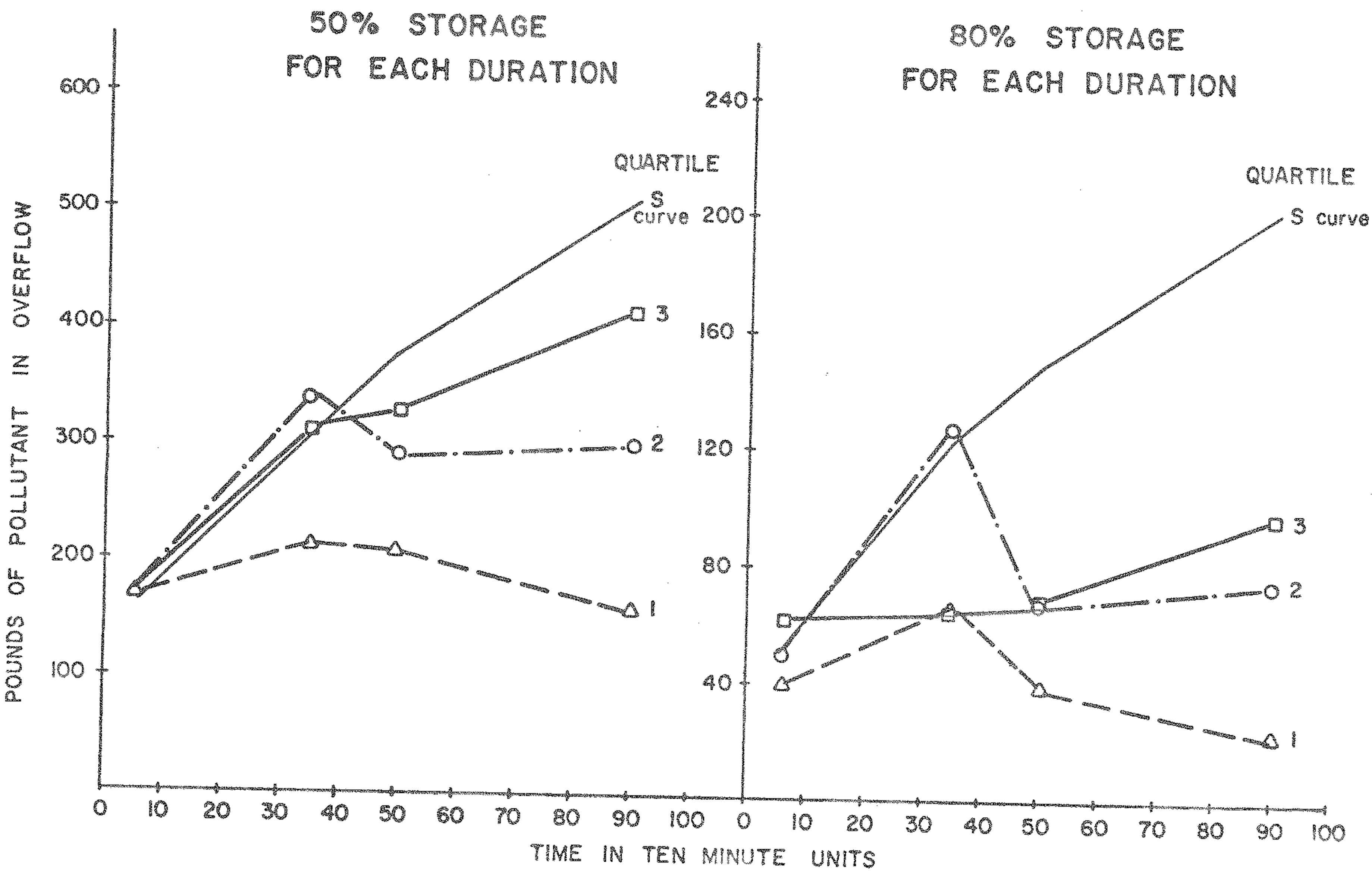


Figure 8.10 Time Distribution of Pollutant Overflow for Different Quartile Storms and for Different Storage Capacities

Such conditions as storms of significant depth occurring close together which require much more storage than the two separately, a significantly higher runoff-rainfall ratio, and greater than expected storms in terms of intensity and/or depth are not accounted for and are considered minor.

The calibrated STORM model considers all of the above conditions and others, since it utilized a long, twenty years or greater, rainfall record to simulate the runoff and pollutographs from the watershed. A comparison of the storage needs to provide for a given level of treatment calculated by STORM vs. the rainfall storage utilization curve can reflect the relatvie importance of "abnormal" hydrological conditions STORM accounts for.

8.7 COMPARISON OF THE STORAGE UTILIZATION CURVE vs. STORM

Several STORM runs were made using a 22 year rainfall record at the Purdue Agronomy Farm, about six miles northwest from the watershed. The yearly average statistics generated by STORM are presented in Table 8.1. A plot of percent pollutant overflow vs. inches of watershed storage for four treatment rates is compared to the storage utilization curve for 100% treatment in Figure 8.11. There are three principal comparisons to be made. The first is that STORM's percent removal is significantly less than the expected value curve. The explanation of this will be presented later. The slopes of the simulated percent removal are smaller than the

Table 8.1 Storm Output for North, West Lafayette Watershed

Treatment Rate inches/hr.	Storage Capacity inches	Number of Overflows per year	lbs of SS in Overflow per year	% lbs of SS in Overflow per year
.06	.28	1.0	3805	7.7
	.14	2.2	7156	14.5
	.07	3.7	10460	21.1
	.035	5.4	12898	26.1
.04	.28	1.4	4576	9.2
	.14	2.9	8837	17.9
	.07	4.8	12903	26.0
	.035	7.4	15912	32.0
.02	.28	1.9	6044	12.2
	.14	4.0	11685	23.6
	.07	6.8	16812	34.0
	.035	11.8	20746	41.9
.01	.28	2.2	7539	15.2
	.14	5.0	14332	29.0
	.07	8.7	20391	41.2
	.035	17.5	25402	51.3

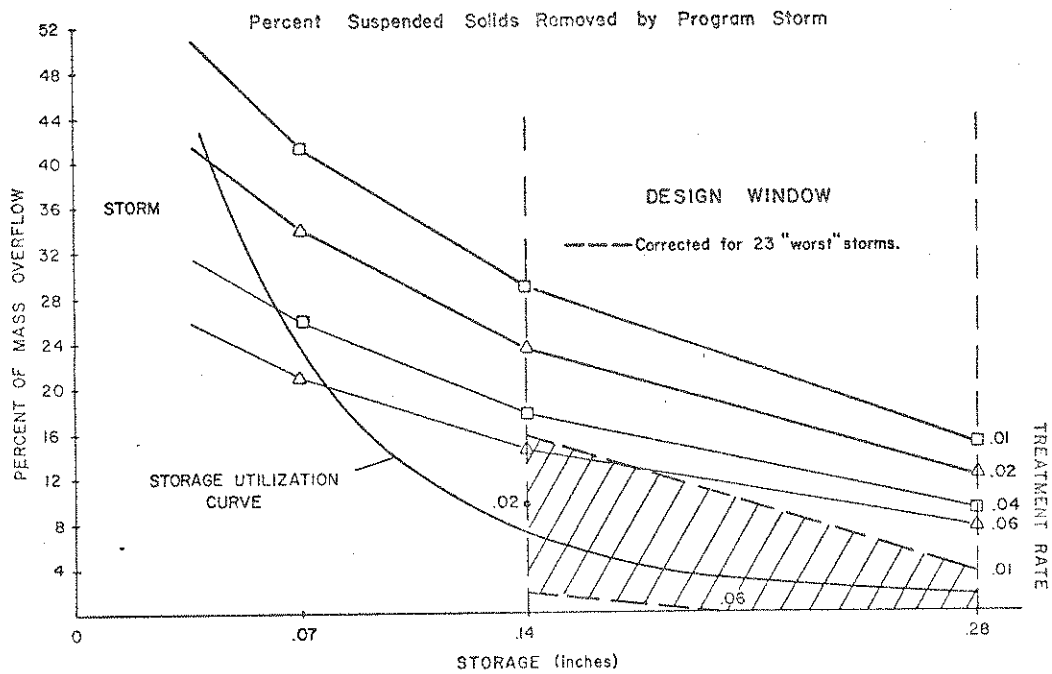


Figure 8.11 Percent of Mass Overflow vs. Storage

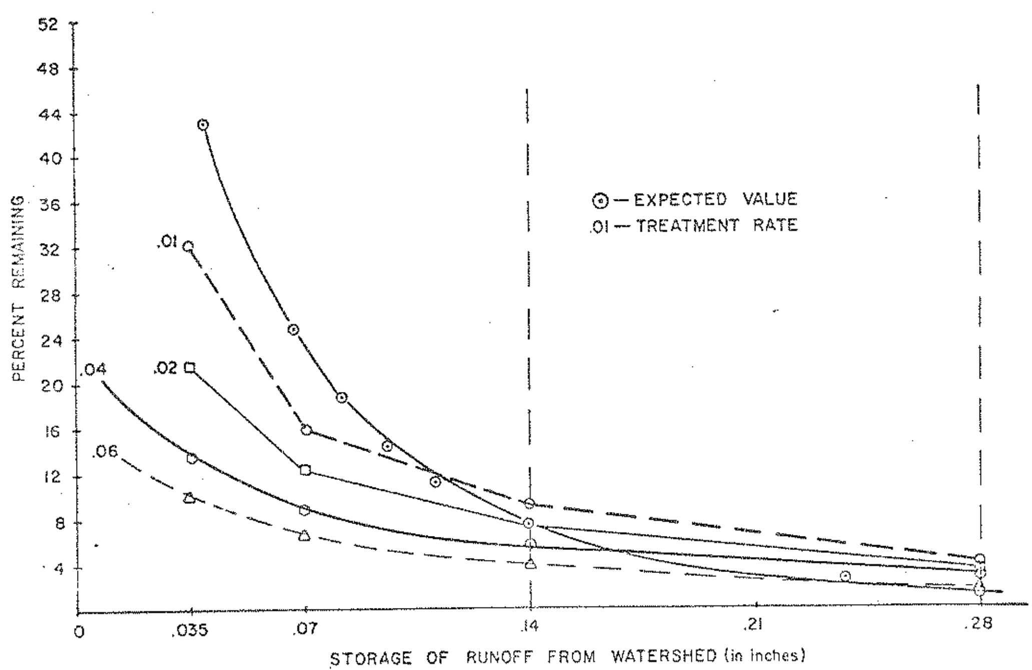


Figure 8.12 Storage Curve Generated from Expected Rainfall Mass Curve

slope of the expected value curve; for storages less than 0.14 watershed-inches. This can be accounted for by the fact that the treatment rate adds significantly to the apparent storage of the treatment system. For example at a storage of 0.035", a treatment rate of 0.01"/hour for 4 hours will effectively double the total treatment capacity. The slopes in the "design window", 0.14-0.28 watershed-inches, are significantly less than the slopes in the lower storage areas. This implies that the removal efficiency is in the economically feasible region, design window, whereby it would take considerably more storage to obtain an appreciable reduction in pollutant overflow. A study by Dendrou and Delleur, Technical Report No. 101, found that storages much above 0.28" are economically unfeasible.

To further examine the relationship between the expected curve and the simulation, a comparison of the expected curve and percent overflow event curves for each treatment rate vs. storage is presented in Figure 8.12. The baseline for total events are not directly related, but they seem to agree on the location of the design window. At 0.28 inches of storage the number of overflows per year range from 2.2 at a treatment rate of 0.01 in/hour to 1.0 overflow per year at a treatment rate of 0.06 in/hour.

The plots in Figure 8.13, illustrate the fact that the storage and not the treatment rate is the principal component of the system responsible for significant reduction in overflow events. Since treatment plant costs are usually much more than storage facilities, one can economically minimize overflow events using a relatively small treatment plant.

8.8 ANALYSIS OF THE WORST EVENTS AND THEIR EFFECT ON THE ANALYSIS

A treatment rate of 0.06 with 0.28 in. of storage produces only one overflow/year, accounting for 8% of the total pollutants. Since these events are so infrequent and difficult to treat, they should be disregarded in a stormwater treatment design. These events could bias the analysis towards more stringent control measures than needed. Also these events cause excess erosion which is untreatable, in farmland, etc. and cause minor flooding problems and other environmental problems which undermine the effect of treatment of the suburban runoff. These storms are plotted in Figure 8.14 for comparison against the expected peak storms and the 5, 10, and 25 year storms. Seven, or roughly a third, of the worst storms are more intense than the five year storms. All but three lie above the expected peak storms, estimated from the regression equation developed in Technical Report No. 55, cited previously. A plot of the total suspended solids vs. depth supports the assumption that the total pollutant level can become independent of depths of the events; i.e. a finite amount of pollutants exist on the watershed (Figure 8.15). There are three "outlyers" which could be attributed to STORM's sensitivity to very intense rainfall peaks as experienced in the calibration process (could have > 20% error on a single storm and still be within 3-4% for total S.S.).

8.9 ANALYSIS OF THE OVERFLOW EVENTS WITHOUT THE 23 WORST STORMS

For this analysis, five conditions were examined. They are: 0.01 inches/hour treatment rate with 0.14 and 0.28 inches of watershed storage, 0.02 inches/hour treatment rate with 0.14 inches of watershed storage, and 0.06 inches/hour treatment rate with 0.74 and 0.28 inches of watershed storage. The 23 worst storms were identified in each case and recorded separately. The distribution of the remaining overflows are plotted and compared to the other 23. A new percent removal value is calculated by subtracting out the 23 worst from the total suspended solids and the overflow values. The data is illustrated in Figure 8.16. The profiles of the overflows reveal that the 23 most difficult storms to treat do, in fact, introduce considerable bias into the percent removal analysis. These storms are considerably more severe in their pollution potential. The table below summarizes the differences in the percentages between the original and adjusted overflow.

The percentage of suspended solids in the overflow are clearly influenced by the 23 worst events; especially in the design window where at least 56%

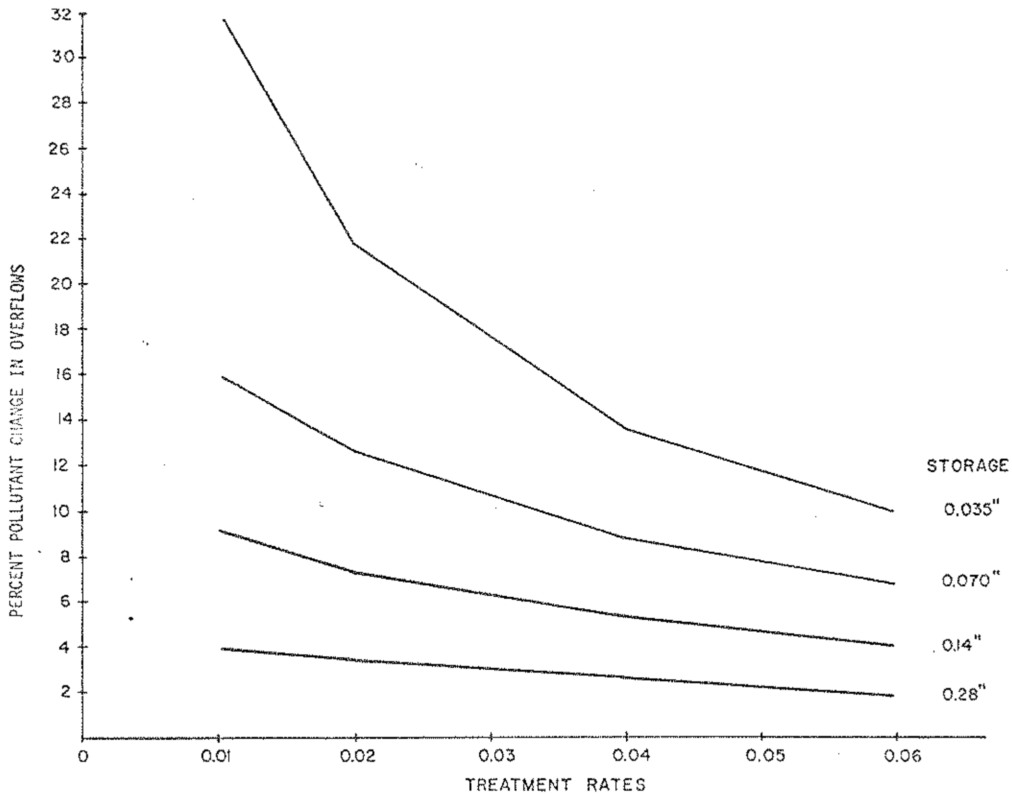


Figure 8.13 Percent Pollutant Change vs. Treatment Rate at Constant Storages

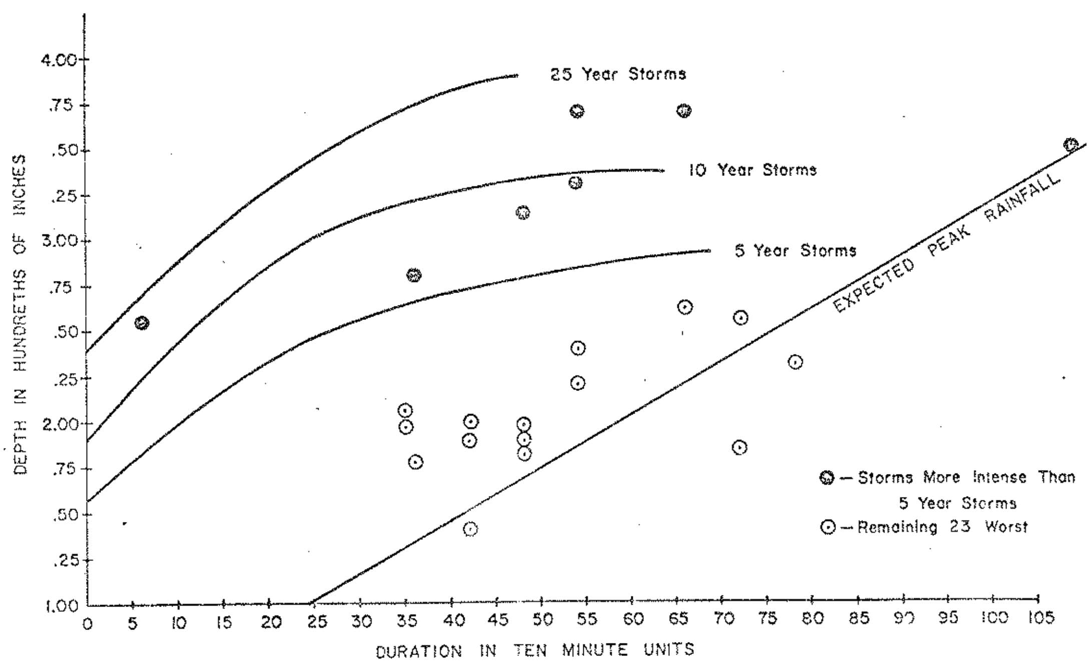


Figure 8.14 23 Worst Storms Compared to Expected Peak

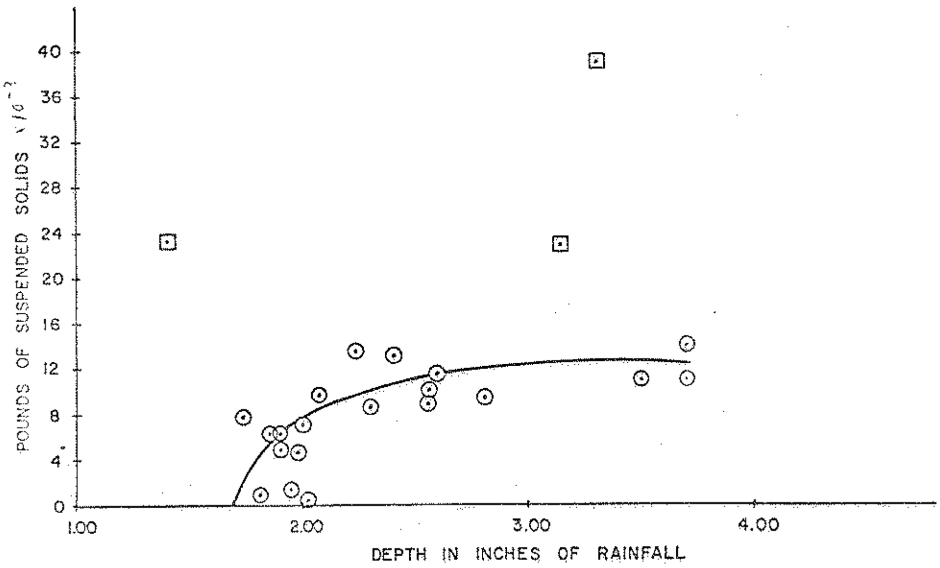


Figure 8.15 Total Pounds of Suspended Solids vs. Depth of Rainfall Event for the 23 Extreme Events

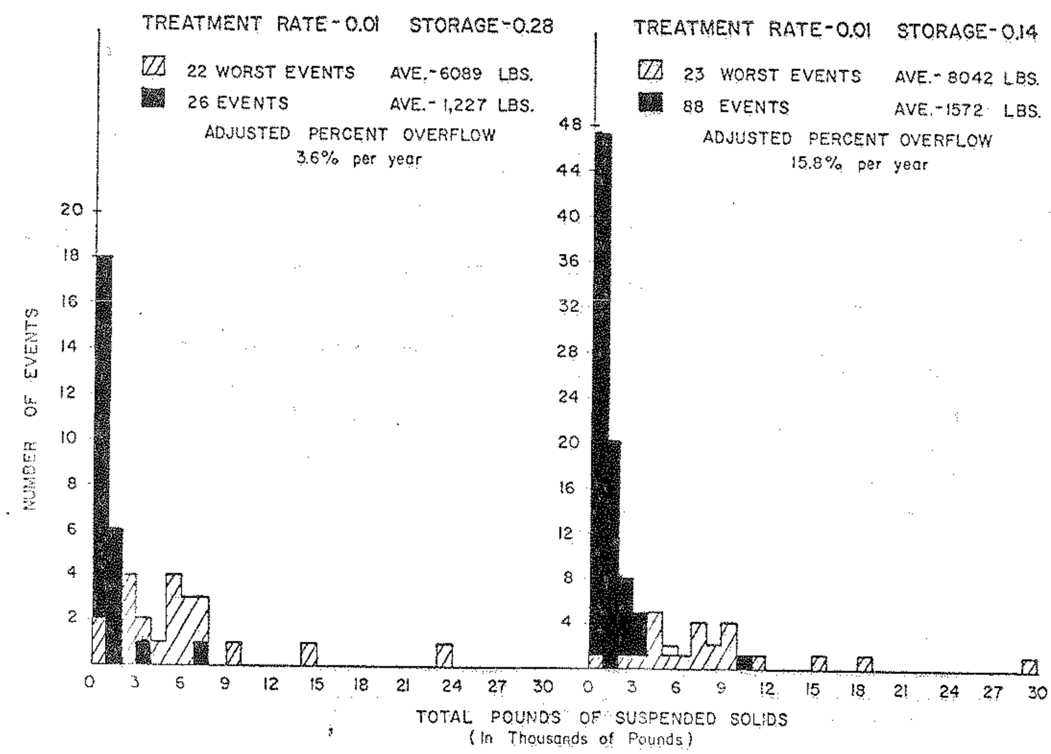


Figure 8.16 Distribution of Suspended Solids by Events

Treatment Rate	Storage Capacity	STORM % of SS in Overflow	Adjusted % of SS in Overflow	Percentage of SS in 23 Worst
0.06	0.14	14.5	1.8	84.6
0.06	0.28	7.7	0.0	100.0
0.02	0.14	23.6	9.7	64.8
0.01	0.14	29.0	15.8	56.1
0.01	0.28	15.2	3.6	80.8

of the overflow can be attributed to these storms. If one plots the adjusted percentage overflows and compares their profiles to that of the storage utilization curve, it becomes evident that the proposed "design window" is an adequate estimator of the expected pollutant overflow.

8.10 STORMWATER RUNOFF WATER SAMPLING METHODOLOGY

Analysis of the field data obtained during the study allowed for the development of sampling and analysis methodology for stormwater runoff.

It was found that an automatic sequential composite sampler (e.g. a N-Con "Sentry" sampler) in conjunction with a liquid level control was adequate for obtaining samples of stormwater runoff. Such a sampler permitted almost continuous sampling of runoff events by collecting individually composited samples which represented a sub-period within the overall sampling period. This continuous sampling, even during individual samples, was made possible by adjusting the length (duration) and number of pumping cycles. Such a sampler permits one to obtain data in regard to "first flush" phenomena. Without such automation, these important data are lost.

Sampling frequency has a measurable effect on the peak value of the pollutograph. Decreasing the sampling frequency decreases the peak value by as much as 40 percent. The sampling frequency has little effect, however, on the shape of a pollutograph except at the peak. The collection of between 1,000 and 1,500 milliliters of sample once every half-hour has been determined as the most appropriate sampling scheme.

The quality of the baseline (dry weather) flow and the conditions in a storm sewer at the start of a rainfall event has an effect on the quality of initial runoff, particularly during very low flows. This is a good reason for monitoring the "first flush" phenomenon of a runoff event. It was found that for a given stormwater runoff event, the pollutograph generally has a shape which is characteristic of the hydrograph. This indicates that flow is the most important contribution to the pollution loading from a stormwater runoff event.

The decision as to the sampling duration for any particular storm must be made by the investigator at the time of sampling. Whether or not sampling need be continued beyond 6 hours, for example, must be based on subjective observations of the investigator. Such observations include: 1) visual note of turbidity of the samples; 2) whether one has a rising or falling stage as indicated by flow recorder; and 3) information on weather conditions.

8.11 CONCLUSIONS

From the comparison of the water quality simulation using STORM with the expected storage utilization curve, it is clear that expected conditions are relevant design criteria. The STORM program provides useful information regarding treatment, storage, and water quality scenarios. The expected storage utilization curve could be used as a check of the validity of the output from STORM. If the program is properly calibrated, one would expect that the family of Storage-Treatment-Overflow curves will resemble the storage utilization curve.

From an economic viewpoint the optimal number of overflows appears to be between four and five per year. The analysis was performed using the global economic analysis developed by Dendrou et al., Technical Report No. 101*. The overflow data for a given storage and treatment rate is plotted on the storage-treatment-economically feasible surface, see Figure 8.17. From this figure one can see that restricting a watershed to 1-2 overflows per year would not be cost efficient at all. From the economics analysis performed by Miller in this report, it is apparent that storage is a more cost effective measure in reducing the number of overflows than increasing treatment capacity. Therefore, in the case of a need to compromise from the optimal storage-treatment combination, preference should be given to storage. Fortunately, it appears that the optimal number of overflows per year on an economic basis corresponds to the optimal number of overflows based on water quality. This can be seen by observing the family of overflow curves generated by STORM. The number of overflows versus storage-treatment obeys the law of diminishing returns.

Overall, STORM, if properly calibrated, can provide reliable information for planning decisions.

Dendrou, S. A., Delleur, J. W. and Talavage, J. J., "Urban Storm-Drainage Systems Planning," Purdue University Water Resources Research Center, Technical Report No. 101, 1978.

8.12 PUBLICATIONS

For further details on the comparison between the probabilistic approach and the model STORM for the planning of urban drainage storage and treatment facilities the reader is referred to the following publications:

PWRRC Tech. Rept. 105, "Simulation vs. Probabilistic Approach for Evaluating Storm Water Treatment Alternatives," by W. Melville and J. M. Bell, June 1979.

Thesis, "An Evaluation of Watershed model STORM for Management of Stormwater Runoff," MSCE Thesis by W. Melville, Purdue University, Aug. 1979, Dr. J. M. Bell, Major Professor.

For further details of the development of sampling and analysis methodology for stormwater runoff, the reader is referred to the following publication:

PWRRC Tech. Rept. No. 64, "Sampling and Analysis of Stormwater Runoff from Urban and Semi-Urban/Rural Watershed," by F. T. R. McElroy, C. F. Mattox, D. W. Hartman, and J. M. Bell, Sept. 1976.

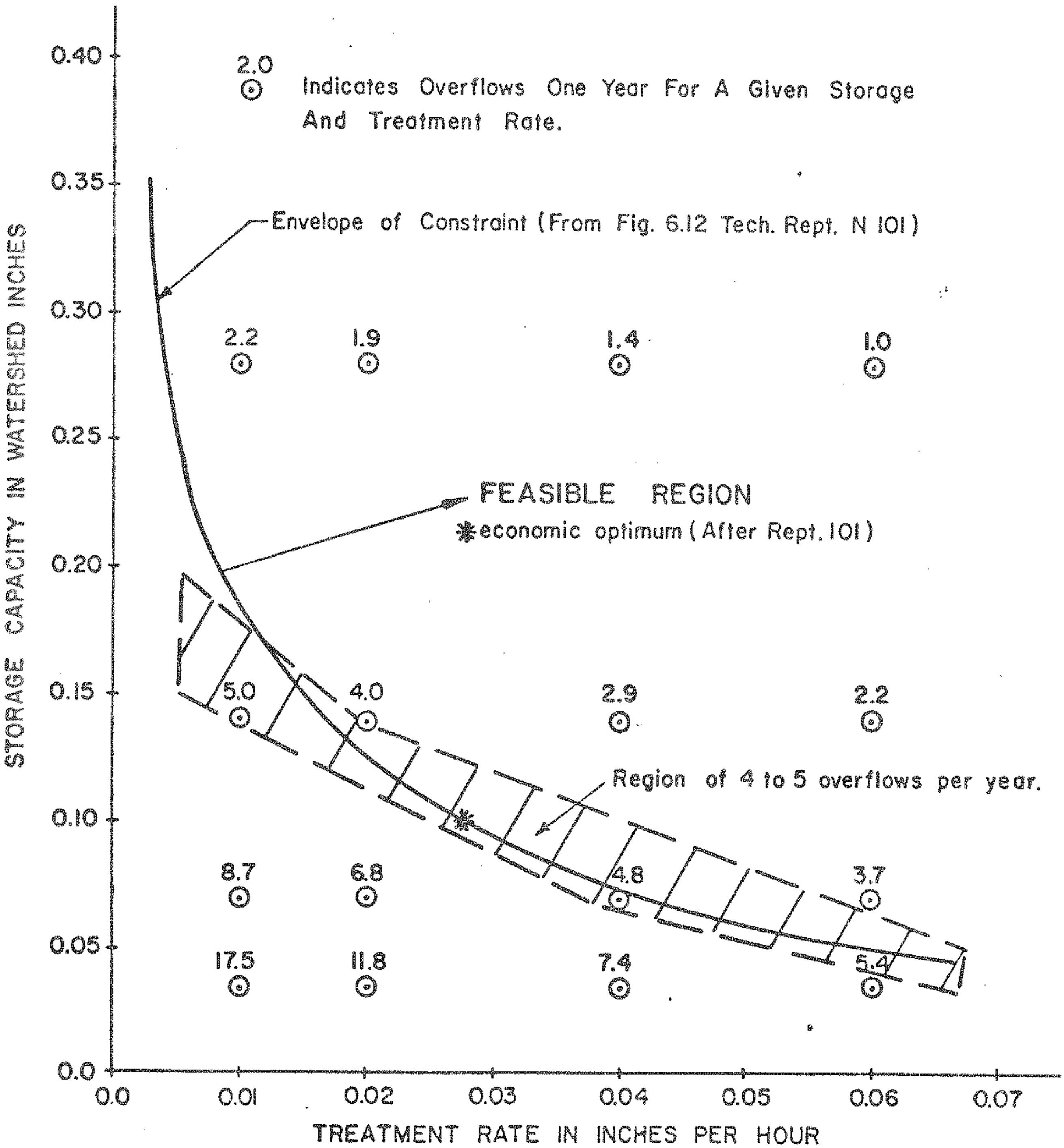


Figure 8.17 Comparison of the Number of Overflows to the Global Economic Analysis of a Northwest Lafayette Watershed

Chapter 9
Economic Impact of Alternative Stormwater Drainage Systems

9.1 INTRODUCTION

Expanding urban communities are faced with continual decisions about the type and scale of drainage systems to develop in new subdivisions. The need for economical systems that provide rapid movement of stormwater off of the streets is essential to insure minimum property damage from storms. In addition communities are becoming more concerned about the quality of stormwater that is carried from the yards and streets into the drainage system. As pollution control regulations become more stringent it may be necessary to improve the quality of the stormwater before it is released to the receiving stream. This raises further questions for communities about the interaction between the type and scale of treatment facilities in relation to the type and scale of drainage systems. Questions are continually raised about the use of detention storage facilities and the role they might perform in reducing the overall cost of drainage system design. The least cost system is not the only economic question of concern to the community. They are equally interested in the income and employment generated in their community through the construction of drainage systems.

This research (Phase II of the Purdue Urban Water Project) attempts to examine these issues in the context of a medium size urban area. Alternative drainage systems are designed and compared to determine the impact of different types and scales of systems upon the cost of the system and the income and employment in the community generated from its construction. A watershed in Tippecanoe County, Indiana was selected to explore these issues.

A) *Objectives*

The general objective was to explore the methodology and measurement of wastewater drainage systems with and without wastewater treatment facilities for medium size urban areas. This exploration sought to improve the methodology to measure, refine the measurement, and evaluate the policy implications of alternative drainage systems. Particular attention was directed to evaluation of both the direct and indirect economic impact of alternative system designs.

The specific objectives were:

(1) to measure and compare the direct cost of alternative systems of drainage and wastewater disposal in a watershed in Tippecanoe County, Indiana, and,

(2) to develop improved methodology to measure the indirect economic impact of the alternative systems developed in objective one.

9.2 METHODOLOGY AND DATA BASE

A) *Engineering Systems Design*

Fifteen alternative systems have been designed for the drainage portion of the engineering analysis. These designs are outlined in Table 9.1. The range of designs selected permitted a comparison of rural drainage systems, urban drainage systems with a open channel section and urban drainage systems that were entirely pipelines. The urban systems were evaluated for single family housing only. Twelve of the 15 designs examined had different scales of detention storage and different numbers of detention facilities. Emphasis was placed on detention storage in order to permit evaluation of the detention storage in relation to different scales of treatment plants that will be described later.

All these systems were designed for a 1912 acre watershed in Northern West Lafayette, Indiana.

The pipe sizes were determined for the different systems through the use of ILLUDAS (The Illinois Urban Area Drainage Simulator) described in the Hydrology section of the report.

Table 9.1 Alternative Drainage System Designs

System Designation	Urban Rural	Volume of Detention Storage (cubic feet)	Number of Detention Storage Facilities	Peak Runoff (cfs)
A	R	0	0	855
B	U[a]	0	0	1384
C	U	0	0	1316
D	U	241,000	1	832
E	U	241,000	2	840
F	U	241,000	3	848
G	U	482,000	1	705
H	U	482,000	2	709
I	U	482,000	3	716
J	U	963,000	1	535
K	U	963,000	2	529
L	U	963,000	3	513
M	U	1,926,000	1	N/A
N	U	1,926,000	2	N/A
O	U	1,926,000	3	N/A

[a]This design was a 3000' long open channel section at the outflow of the drainage system. All other systems are entirely sewers.

An evaluation of the water quality of runoff from the watershed under study is another facet of this integrated study. The STORM (see Hydrology section) model was utilized as the methodology for the water quality evaluation. The storm model was based on 22 years (1953-1974) of hourly precipitation from a climatological station located 6 miles from the watershed.

The West Lafayette watershed was evaluated for four treatment rates. These rates were plants with capacities of 75 MGD, 50 MGD, 25 MGD and 12.5 MGD. This range of treatment rates was selected to encompass the full range of levels of detention storage that was considered in the research, i.e. zero to 1,926,000 cu. ft. of storage.

9.3 DIRECT ECONOMIC IMPACT

Two models were used to evaluate the economic cost of the alternative systems. A simulation model was developed to test the sensitivity of the cost of the drainage systems to variation in the level of operating and maintenance costs. This model calculated the present value of the capital, operating and maintenance cost of each system. An annual average cost model was used to evaluate the combination of drainage system and treatment plant costs. Properly formulated these two models will give identical cost rankings among the alternative systems, so the choice between them is solely convenience of use in the particular situation.

The present value model is specified below:

$$PVC_i = C_i + (M_i/r) - M_i$$

where: PVC_i is the present value of the cost stream for system i

C_i is the construction costs for system i

M_i is the constant stream of annual maintenance costs for system i

r is the rate of interest

This formulation assumes all construction costs occur in the first year and a constant stream of annual operating and maintenance costs begins in the second year.

The total cost of the drainage system includes the cost of pipes, excavation, installation, concrete structures, land purchase, and fencing around the detention ponds. All cost data used in this study are 1977 costs.

Since cost information for annual operating and maintenance were not available, it was assumed to be proportional to construction costs of pipe, detention storage, and open channels. These proportions were assumed to be highest for detention storage, and open channels. Combinations of operating and maintenance cost assumptions ranging from 1% to 20% were examined and the results compared to the initial set of assumptions to test model sensitivity.

9.4 INDIRECT ECONOMIC IMPACT

The construction of a water drainage system would directly provide additional employment and income to the construction industry. In addition, there would be indirect effects on other sectors of the local economy. The impact of these rounds of spending on output, income, and employment in the county would depend on the structural interdependencies between sectors in the economy.

9.5 ANALYSIS OF ENGINEERING SYSTEMS

Pipe sizes respond as expected when the scale of detention storage facility is increased. Larger detention storage decreases required pipe sizes which reduces system pipe cost. System P which has the largest volume of detention storage and the greatest number of facilities has the smallest average pipe diameter of the urban systems. The only system with lower average pipe size than P is system A which reflects the lower runoff associated with rural rather than urban land use.

The STORM model provided additional information that is valuable for selecting the scale of treatment plant and type of detention storage facility. Table 9.2 presents the average number of overflows with four alternate treatment rates for the sets of system designs that have similar storage capacity. If a 12.5 MGD treatment plant is provided for the stormwater in this watershed, the 241,000 ft^3 of detention storage that is provided in systems D, E, and F will result in 17.5 overflows annually. From the data presented in Table 9.2 it appears that the systems most likely to be acceptable from the rate of overflow standpoint (say less than 4 annually) are those systems with the larger treatment plants and/or the larger detention storage facility. This suggests that the key economic tradeoff will be between the cost of detention storage and the cost of treatment.

The output of the STORM model provides insight into the type of detention storage that is most apppropriate. Table 9.3 indicates the maximum age of water stored in the detention facilities in relation to the rate of treatment and detention storage capacity. Although the range of maximum storage time varies from 38 to 1 hours, the most important feature of the table is the relatively small number of hours of storage under most conditions. This indicates plants, such as grass, would be able to grow in the facility which provides the opportunity of building a shallow detention facility within a park

Table 9.2 Average Number of Overflows per Year with Alternative Treatment Rates and System Designs

Systems/ Storage Capacity	Treatment Rate			
	12.5 MGD	25 MGD	50 MGD	75 MGD
DEF/ 241,000 ft^3	17.5	11.8	7.4	5.4
GHI/ 482,000 ft^3	9.5	6.8	4.8	3.7
JKL/ 963,000 ft^3	5.0	4.0	2.9	2.2
MNP/ 1,926,000 ft^3	2.2	1.9	1.4	1.0

Table 9.3 Maximum Age of Storage in Hours on a First In/Last Out Basis

Systems/ Storage	Treatment Rate 12.5 MGD TEV[a]/TOV[b]	25 MGD TEV[a]/TOV[b]	50 MGD TEV[a]/TOV[b]	75 MGD TEV[a]/TOV[b]
DEF/241,000 ft^3	3.2/6.7	2.4/3.7	1.3/2.0	1.2/1.7
GHI/482,000 ft^3	4.1/11.3	3.1/6.7	1.8/3.5	1.6/2.6
JKL/963,000 ft^3	5.1/19.9	3.8/11.0	2.4/6.1	2.1/4.2
MNP/1,926,000 ft^3	6.1/38.6	4.6/20.0	2.9/10.2	2.4/7.1

[a]TEV is the average of total number of events.

[b]TOV is the average of total number of overflows.

that can be used for recreational purposes most of the time. This approach and the alternative single purpose concrete structure are both explored in this study.

9.6 DIRECT ECONOMIC RESULTS

The cost of pipe for the system under study is largest at $4,250,730 in the urban system with 241,000 ft^3 of detention storage and smallest at $3,981,810 in the urban system with 1,926,000 ft^3 of storage in two detention facilities (see Table 9.4).

Costs related to detention storage rise from zero in the no detention storage system to a high of $625,261 in the 1,926,000 ft^3 storage system with two concrete detention facilities. The increasing costs occur for the land acquisition, excavation, concrete, and fencing around the facility.

The sum of pipe costs and detention storage facilities is lower for the systems which do not contain detention storage, i.e., urban sewers rural sewers, and urban open channel. This indicates that the lower pipeline costs which occur when detention storage facilities are added are more than offset by

Table 9.4 Capital Costs of Alternative Drainage System Designs

System Designation	Pipe Cost	Total Cost With Concrete Detention	Total Cost With Grass Detention
A	$3,744,250	$ N/A	$ N/A
B	3,950,860	4,093,620 [a]	N/A
C	4,220,280	N/A	N/A
D	4,250,730	4,354,534	4,309,639
E	4,250,730	4,365,762	4,321,934
F	4,273,305	4,398,603	4,350,855
G	4,201,214	4,357,824	4,304,683
H	4,201,215	4,400,132	4,314,085
I	4,223,790	4,424,290	4,347,747
J	4,129,320	4,441,607	4,339,155
K	4,129,320	4,429,929	4,327,945
L	4,124,825	4,510,929	4,336,872
M	4,030,760	4,574,711	4,376,797
N	3,981,810	4,607,071	4,402,359
P	3,996,445	4,582,889	4,382,968

[a]concrete lined open channel for one branch and reach.

the detention storage costs. Some difference occurs in the extent of this increase in cost between the deep concrete lined detention facilities and the shallow grass lined detention basins. The capital costs of the system are $354,431 more costly for the largest detention storage in comparison to the urban no detention storage pipeline when concrete is used, but only $156,517 more costly with grass.

The most economical number of detention storage facilities (with concrete) in three of the four scales of storage examined was the single detention facility. This occurs due to economies of scale in excavation and concrete construction for the single facility over the two or three unit facility.

Treatment plant costs are presented in Table 9.5. These costs have two important characteristics which influence drainage system design. The first is significant economies to scale as the size of treatment plant increases. It is cheaper per MGD treated to use a larger rather than a small treatment plant. The second characteristic is the sensitivity of the total cost to community of the size of plant. For a given size of community, it costs least to use the smallest treatment plant possible that will treat most storms totally with only an occasional overflow from an unusually large storm.

These two characteristics encourage either (1) regional treatment where several communities combine their wastewater to take advantage of the economies of scale per MGD treated associated with large plants, or (2) for the individual community

Table 9.5 Treatment Plant and Total System Annual Costs

System Designation[a]	Treatment Rate	Annual Cost Drainage[b]	Annual Cost Treatment[c]	Total Annual Cost
	(MGD)	(dollars)		
C1	12.5	253,478	866,876	1,120,353
C2	25	"	1,368,750	1,622,228
C3	50	"	2,190,000	2,443,478
C4	75	"	3,011,125	3,264,603
D1	12.5[d]	264,675	866,875	1,131,550
D2	25[d]	"	1,368,750	1,633,425
D3	50[d]	"	2,190,000	2,454,675
D4	75	"	3,011,125	3,275,800
G1	12.5[d]	268,790	866,875	1,135,665
G2	25[d]	"	1,368,750	1,637,540
G3	50	"	2,190,000	2,458,790
G4	75	"	3,011,125	3,279,915
K1	12.5	279,608	866,875	1,146,483
K2	25	"	1,368,750	1,648,358
K3	50	"	2,190,000	2,469,608
K4	75	"	3,011,125	3,290,733
M1	12.5	297,136	866,875	1,164,011
M2	25	"	1,368,750	1,665,886
M3	50	"	2,190,000	2,487,136
M4	75	"	3,011,125	3,308,261

[a]The numbers 1 through 4 indicate the size of treatment plant consistent with the rate in Column 2.

[b]Capital cost amortized for 50 years at 5 1/2% plus O+M cost at 1% on pipeline and 10% for detention storage. Based on the grass detention storage facility.

[c]Capital cost amortized over 30 years at 5 3/8% plus O+M cost at 5% of the capital cost. (Monti, 1974)

[d]These systems are not acceptable because they have an excessive number of overflows (see Table 9.3).

the introduction of detention storage facilities in the drainage system to even out the flow, reduce the maximum CFS of flow, and achieve the lower total cost for the community associated with small scale treatment plants.

When treatment plant costs are added to the drainage system costs the detention storage facilities become economically viable as components of system design. Without treatment plants drainage systems without detention storage were least expensive, but with treatment plant costs included the drainage systems with detention storage facilities are least expensive (see Table 9.5). This conclusion holds for both detention storage facilities with concrete and grass lined storage. This occurs because the cost of treatment plants in this scale of operation completely dominates the cost of the drainage system.

A) Indirect Economic Results

From the I/O model of Tippecanoe County, output, employment, and income multipliers were calculated. Each multiplier is computed differently, yet all are generated from the sectoral interdependencies in the model (direct, indirect, and induced linkages). These costs are considered to be exogenous increases in the sales of the construction industry. Hence, the construction industry sector multipliers are used to determine the output, employment, and income effects from the construction of any one of these drainage systems.

The output multiplier for the construction industry sector is 1.760 meaning that one dollar increase in construction sales will have a $1.76 impact on the total output of the economy. This multiplier is the fifth highest of the 19 sections reported which indicates changes in construction spending have a relatively large impact on the total output of the economy in comparison to an equal change in most of the other sectors.

The output effects from the construction of each drainage and treatment system is determined by multiplying the total cost of each system by the construction multiplier. Table 9.6 summarizes the output effect for each of these systems. Since the system with the greatest total cost has the greatest impact on output, those systems with no detention

Table 9.6 Output and Employment Effect of Alternative Drainage and Treatment Systems

System[a]	Output Increase (dollars)	Employment Increase (jobs)
A4[b]	$47,759,881	1176
B4[b]	48,383,786	1192
C4[b]	48,609,976	1197
D4	48,769,553	1204
E4	48,791,509	1204
F4	48,843,156	1205
G3	38,045,902	939
H3	38,062,710	940
I3	38,122,806	941
J1	21,142,291	525
K1	21,113,415	524
L1	21,138,286	528
M1	21,209,584	531
N1	21,255,232	532
P1	21,220,604	531

[a]The systems selected for indirect analysis include those with the smallest scale of treatment plant that has an average overflow of less than 5.5 times annually.

[b]These three systems have no detention storage and would require treatment plants larger than 75 MGD to achieve an average annual overflow level of 5.5 or less.

storage and very large treatment plants have the greatest effect upon the Tippecanoe County economy.

9.7 CONCLUSIONS

When urban development occurs the least costly drainage system involves combining some of the open channel drainage systems with enclosed storm water pipes from the new subdivisions. This is still the least expensive system even when the open channels must be lined with concrete to maintain bank stability and to increase the increasing rate of flow in the channel due to the development of an urban rather than rural hydrograph. The water quality changes as urban development occurs because different types and concentrations of pollutants occur in the runoff from watersheds with large areas of low or zero permeability land surface. With the loss of soil as a living filter further deterioration of water quality may occur.

The urban drainage system can be developed with or without detention storage capacity in the system. Complete pipeline systems with no open channels that have detention storage are more costly than pipeline systems without detention storage. The reduced cost of pipe because lower sizes are possible is exceeded by the additional cost of detention storage. This relationship holds whether the detention storage is one large facility or several smaller facilities distributed throughout the watershed. Detention storage is still more costly than pipelines alone even when the storage is a low grass area in a recreational park rather than a concrete lined facility.

This research indicates that the number of detention storage facilities is a positive function of cost in most cases. Therefore, a single facility is generally less costly than multiple detention facilities in the watershed. With very large volumes of detention storage the number of facilities has strong interaction with the location of the facility so the economically least expensive system is a joint function of size, number, and location.

There may be two situations which will encourage the use of detention storage even though it is more costly than pipeline systems alone. A change in the hydrograph may not be permitted when rural areas are changed to urban through development because of concern about flood damage. Zoning and subdivision development regulations that reflect this concern, force a developer to include some type of detention storage facility to meet this requirement. This research indicates that substantial (and costly) detention storage may be required in order to match the urban with the previous rural hydrograph.

A second situation develops when water quality is an important concern. When the quality of runoff from the urban area becomes a critical problem, the combined cost of drainage and water treatment results in different cost conclusions than when drainage is the only important consideration. The high capital cost of treatment plant construction and the equally high cost of operation indicate that the cheapest complete system will include detention storage facilities. The reduction in cost that results from the installations of a smaller treatment plant exceeds the cost of providing the detention storage facilites.

The indirect economic impact is directly proportional to the direct cost of drainage system development. During the period of construction of drainage facilities output and employment in the community is greatly increased. For example, a 12 million dollar construction project generates 21 million in total output in the community and creates additional employment for 524 people in all sectors.

9.8 PUBLICATIONS

For further details regarding the economic impact of alternative stormwater drainage systems the reader is referred to the following publication.

PWRRC Tech. Rept. 111, "Economic Impact of Alternative Storm Drainage Systems," by W. L. Miller.

Chapter 10
Evaluation of Acceptability of Urban Water Policies

10.1 Introduction

The purpose of this part of the study is to evaluate the acceptability of selected urban water resources policy alternatives, to both community leaders and to the general public. The implementation of water projects requires the acceptance by such people. This may be a fairly routine matter for most smaller projects, but for larger ones there may be considerable discussion by leaders and residents with some disagreement or conflict over whether a project is necessary or whether a specific proposal is the best plan. We focus on a series of related issues concerning drainage, land use, urban growth and environmental quality. The issues deliberately vary from being quite specific to quite general. The reason for this, as well as the other comparisons in the analysis, is the overall methodological orientation of the study. While we do examine substantive issues, we are as concerned about the methodological approach used and its potential for more general application.

The development of urban areas in general, and more specifically those aspects involving water resources, require public policy decisions. As such, the preferences and perspectives of community residents become factors in decisions, in addition to factors of cost, technical feasibility and enviromental quality or public health. Major water resource decisions, such as upgrading treatment plant facilities which is now occurring in many areas, affect the whole community, and often surrounding areas as well. The increased costs for such facilities is borne by residents and industries that are served by them. Additionally the extension of water supply and sewer lines into rural areas are significant factors in the direction of growth for cities. A final example is the development or preservation of wet lands and flood plains.

Community leaders in official positions such as mayors, city councilmen, or county commissioners must act on most of these policy decisions. Other public officials, such as engineers, health officers and planners, are regularly involved in making and implementing decisions. Other community leaders, such as heads of businesses and industries, are often very concerned about such decisions as major users of water and sewage facilities, or in terms of the effects such decisions may have on the growth potential of the area.

Citizens generally are affected by these decisions. The construction of major facilities, or their expansion, is very costly, and often represents a large increase in user charges or taxes for residents. There may be policy questions concerning the distributions of these charges, either areally or through a graduated rate structure. Residents may have different views about the importance of environmental quality or construction in flood plains.

Obviously not all citizens or leaders become involved in every water resource decision in the community. But when they feel they have a substantial interest in the outcome of a decision, the probability of their involvement increases. It may also increase if they feel their participation may influence the decision outcome.[1]

10.2 The Research Method

Conceptually the purpose was to evaluate the acceptability of alternative water resources policies among community leaders and the general public.

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[1] *For a detailed discussion of the theory underlying this perspective see Peter V. Marsden and Edward O. Laumann, "Collective Action in a Community Elite." Pp. 199-250 in Roland J. Liebert and Allen W. Imershein (eds.), Power, Paradigms and Community Research, Beverly Hills, CA, Sage Publications, 1977.*

There are many implicit problems in this. For example: How specific should the policy alternatives be? How many should be posed? How important are these issues perceived to be compared to other community issues? How familiar with and knowledgeable about water issues are people?

The approach taken assumes that water policy decisions at the community level are pragmatic, and not made in the abstract. Among other things, this implies that water "problems" are rated in importance in comparison to other problems, recognizing that this rating is usually informal rather than formal. Decisions are likely to be made only when there is a rather immediate need, such as an inadequate supply or a mandatory requirement for improved treatment facilities. Additionally, detailed plans are likely to be specific to each community; it is among the basic or more general alternatives where comparability might be found across communities. That is, methodologically we might be able to develop approaches that would be useful in different cities at this more general level.

We chose to vary the specificity of questions, asking more detailed questions about drainage - paralleling the other parts of the study. Somewhat more general questions were asked about land use and urban growth, and the most general questions were asked about pollution or environment.

Knowledge or familiarity with issues was considered, also. One reason is that this affects a person's present position on an issue. People who have experienced flooding or low water pressure may feel differently about policy questions than those who have not. Simple factual questions, e.g., where does your drinking water come from, tell something about the importance attached to an issue by whether persons know the answer or not. Another reason is that as an issue becomes more salient in a community and people acquire more experience or knowledge about it, their position on the issue may change. (We only gathered data at one point in time; however, that might not be sufficient in many cases where change may be occurring.)

We also sought some information on variables that may be indicative of persons participation in the policy process. This set of questions concerned whether they follow governmental activities in the news media, whether citizens should or should not get involved and whether they have been involved.

This conceptual approach lets us look at citizens' and leaders' perspectives on water resource policy issues, and also at factors which may help us understand differences in those perspectives.

The data for this study were gathered by personal inverviews. The interviews generally took 30 to 45 minutes. The sample of the general public was a stratified area probability sample. The eight townships in essentially the northeast half of Tippecanoe County, Indiana, were included. This includes the two cities of Lafayette and West Lafayette (1970 populations of 44,955 and 19,157, respectively), and most of the area that is being relatively directly affected by urbanization, particularly land use changes from agriculture to urban uses.

Since the county is a Standard Metropolitan Statistical Area, census tract and block data were available for the urbanized area. Two stratification criteria were used in the sampling plan. One was geographic location, with the categories being (a) urbanized, where land use is most intensive, and population the most dense; (b) transitional, surrounding the urbanized area, where there is some intensive land use but also land changing from agriculture to residential, business or industrial; (the boundaries for these areas did not always follow existing political boundaries, and were somewhat arbitrary); (c) rural, that remaining area outside of the transitional boundaries containing rural and smaller town (less than 1000) residents. The second stratification criterion was social class, using mean housing value by block as reported in the 1970 U.S. Census. While these figures would have been greatly affected by inflation, it was not felt that this would be a highly differential affect, and that their use for placing blocks into high, medium and low categories would be satisfactory. There were two restrictions on the use of the social class criterion: (1) these data were not available for the rural area. Because this was a large area with relatively few persons, it was divided into three sub-areas, north, east,

and south, using township boundaries. "Blocks" of one to two square miles were created as the primary sampling units, following roads. Two blocks were selected within each of the three areas to give geographical spread. "Blocks" had to be created similarly in parts of the transitional area.
(2) Within urban and transitional areas data on housing value were not available for all blocks, because of too few owner occupied housing units within them. These blocks were placed in a fourth stratum called "Not Elsewhere Classified." The number of dwelling units selected randomly within each stratum was proportional to the total number of dwelling units in 1970. Because the number of dwelling units per block varied greatly among strata, it was necessary to use different sampling fractions within strata so that the final selection of dwelling units would be proportional. (Five tracts within the study area are omitted as they had been throughout this study because they comprise Purdue University or an area adjacent to the University that is largely student apartments with turnover in residents).

The sample size selected was 200 adult residents, one per dwelling unit, age 18 or older. This is not a particularly large sample for survey research; it is large enough to provide variation in responses and thus to examine the adequacy of this approach.

The completion rate of 70 percent of the interviews was low in the experience of the principal investigator. A substantial part of this was attributable to just a few blocks in which considerable difficulty was encountered finding residents at home, even though interviewing was carried out into the early evening and on weekends. Three calls were made at a house to obtain an inverview, before replacing it. However, this is a time consuming and costly procedure. These problem blocks were middle class, and rather new houses. We can only speculate about the reasons for this, whether it was some unique situation, around the end of the school year or an increasing number of households with either a single parent or both parents (adults) working.

The sample of community leaders combined both a "positional" and "reputational" approach. Eighty-three different positional leaders were identified. These included mayors, county commissioners, city and county councils, school superintendents, chief executives of businesses with 100 or more employees and members of the Chamber of Commerce Board of Directors. Five leaders, the mayors and county commissioners, were purposively selected because their positions give them the greatest overall view of issues. Thirty-nine, or half, of the remaining 78 leaders were randomly selected. These leaders were asked as one of the interview questions to

Table 10.1 Summary of Sampling Plan

Area and Social Class Strata	No. of Blocks per Strata	No. of Blocks Selected	No. of Respondents Expected	No. of Respondents Obtained
Urban				
High	128	4	19	14
Medium	360	11	53	49
Low	121	4	18	13
NEC[a]	227	7	33	15
SUB-TOTAL	836	26	123	91
Transitional				
High	54	5	23	11
Medium	22	2	9	7
Low	2	1	1	1
NEC[a]	38	3	16	10
SUB-TOTAL	116	11	49	29
Rural[b]	117	6	28	19
TOTAL	1069	43	200	139

[a] NEC: Not Elsewhere Classified - see text for explanation.

[b] Data for social class strata were not available for Rural area.

nominate persons they saw as leaders. Such persons who received two or more nominations were then contacted for an interview.

The initial contact with leaders to be interviewed was a letter from Dr. Dan Wiersma, Director, Purdue University Water Resources Research Center, explaining in general terms the nature of the project. This was followed by a telephone call to set up an appointment.

Of the initial group of 43 positional leaders, 38 were interviewed. An additional 15 persons, who were not among the initial 43, were nominated at least twice. Eight of them were interviewed. Thus, the total number of leaders interviewed was 46.

10.3 Findings

The approach taken here is to move from more general to more specific issues, comparing respondents by whether they lived in the urban, transitional or rural area, or were leaders. The findings are in three parts: (1) attitudes, experience and knowledge; (2) policy issues; and (3) public involvement.

A. *Attitudes, Experience and Knowledge*

One approach to determining how important an issue is in people's minds is to ask a very general question like: "What would you say is the most important problem facing this community right now?" We asked this question very early in each interview. Only three of the 46 leaders and five of the 139 general public respondents felt that some type of water, land use, environment or pollution issue was most important.

The number of people who felt there were at least some environmental problems increased when asked more directly: "Do you think there are any problems with the environment in this area, now or in the last few years?" About 47 percent of both the leaders and the general public said no, there was none. The urban respondents particularly saw no problems (58 percent). In contrast, almost two-thirds of the transition and rural residents generally saw some problems. Of course, slightly more than half of the leaders also saw some problems.

Those respondents who indicated there was any environmental problem were asked how concerned they were about the quality of the environment in this area. Of those who thought there were problems, the majority (73 percent) were somewhat or very concerned about them. Concern among rural residents and leaders was particularly high, with 15 percent of the former being very concerned and 70 percent somewhat concerned. The comparable figures among leaders were 48 and 32 percent.

Two conclusions can be drawn from these data. First, the very general "most important problem" question provides a very different view than the more specific "environmental problems" question of the extent to which people feel there are local environmental problems. It is not surprising that different questions, or the way they are worded, produce different answers. The level of concern question, also a rather specific question, shows that there can be substantial concern even where the number of problems is not perceived to be large. Thus, the very general question may under-estimate the depth of concern respondents have. A second conclusion is the importance of looking at subgroups for possible differences. Overall if all respondents were lumped together there would not be a great deal of environmental concern expressed in these three questions. Leaders differ only a little from the total for the general sample. But when even the single variable of location of residence is considered, and the variation within categoires is included, a different picture emerges.

Four rather typical problems people may have with water are flooding or wet basements, sewer pipes backing up, low water pressure and water being cut off for repairs. Respondents were asked whether they had experience these problems, either in their present homes or elsewhere. Rural residents generally did not report any of these problems. Otherwise there was little variation. Flooding or wet basements were most frequent, reported by 46 percent of leaders and urban residents and 56 percent of transitional residents. Water being cut off for repairs (not because of bill payment problems) was second, varying only from 36 to 44 percent. Drain or sewer pipes backing up was less common, varying from 25 to 28 percent. Low water pressure varied somewhat, with only 4 percent of leaders having experienced that compared to 20 percent of urban and 18 percent of transitional residents. These water problems had not occurred to the great majority of persons, but had to a large enough number to suggest general public awareness of them.

Data on "knowledge" about water supply, prices, quality and treatment were also obtained. While there were in a sense right and wrong answers to these questions, answers could and did vary considerably in degree of precision. Our interest is in obtaining only an estimate of the amount of knowledge, or lack of knowledge. Thus, we report only those who indicated they did not know the answer, or whose answer quite clearly reflected a lack of knowledge. The great majority did know where their water came from; only 27 of the 185 respondents did not or gave non-knowledgeable answers. Twenty-two gave non-knowledgeable responses to the name of their water company, and 26 gave such responses to why tap water has a brownish color to it occasionally. A few more people, 41, did not know where their household sewage is treated. The great majority, generally 80 percent or more, of these less knowledgeable respondents were urban residents. Two additional questions showed less knowledge. "Who is responsible for making decisions concerning the price of water in your community?" We considered the state Public Service Commission the most correct answer (excluding those persons with private systems), but only 11 gave this or approximately this answer. More respondents, 66, attributed this responsibility to city government, and an additional 22 attributed it to the water company/works. In Lafayette water is supplied by a city utility, and rates must be approved by the city council before they go to the Public Service Commission. In West Lafayette, a private utility is the supplier, and it can go directly to the Commission. An additional 44 persons either did not know or gave other answers. In response to "Who is responsible for making decisions concerning the quality of water, that is checking to see that it is safe to drink?" Only 23 named the State Board of Health. An additional 14 said some other or an unspecified state agency. Fifty-nine replied some local official, 19 said "government," 12 said individuals themselves, and 58 either did not know or gave some other answer. Less knowledgeable respondents were distributed throughout all residence areas, and leaders, with regard to water quality. In addition to what these data tell us directly about knowledge of water resource issues of seemingly direct relevance to persons, they say something about how people perceive the decision making process. A large number of respondents think first of local government as responsible for decisions, in this case on water prices and quality. Leaders were only somewhat more likely to think of state government than the general public was. This suggests the importance of local government in people's minds despite the substantial role of state (and federal) government in water resources. Additional data on this point are considered below.

B. *Policy Issues*

There are three sub-parts to this section. The first deals with water pollution, how serious people perceive it to be and whether enough is being done about it. The second topic is land use policy and urban growth. Third is drainage, including how people view retention basins and open ditches, and drainage policy.

Water pollution was not seen as a serious problem by most respondents. When asked "Have you ever been concerned about the quality of your drinking water here?," 83 percent said "no." In response to "How serious do you think water pollution is in Tippecanoe County?," 37 percent said "not very serious," and 18 percent said "somewhat serious." Only 12 percent replied that it is serious or very serious.

Those two questions were followed by two others that were intended to help interpret responses by asking the direction people saw pollution control as going. However, they produced mixed results. A little over half of the respondents saw the problem of water pollution getting better in the next five years, as a result of recent federal and state legislation. About 25 percent saw it getting worse. In partial contrast to that, 48 percent thought current pollution control efforts were about right, and 36 percent thought they were too little. Only 6 percent thought they were too much.

We again sought to determine the locus of government responsibility. This time by asking "Some people say that water pollution is the federal government's problem. Do you agree with this?" Two-thirds of the respondents disagreed, and only 24 percent agreed.

Another approach to assessing how strongly people feel about a public policy issue is to ask how much more they would pay in taxes to deal with the issue. This was done by asking first "Would you be willing to pay more in taxes if the increase would effectively combat water pollution?" Sixty percent said yes, they would. They were asked "How much more would you be willing to pay?" The answer to this was surprising statistically, because it was a very flat distribution, with 13 persons saying $1.00 or less per year, 14 saying $100.00 or more per year, and responses ranging from 12 to 16 for the four intermediate categories. There may have been a social desirability affect operating here. This possibility arises from the fact that on the preceeding question 112 respondents had said yes they would pay more, but on this second question only 81 answered with a specific amount they would pay, a decrease of almost 30 percent in number of respondents, that is, people who thought they should say yes, they would pay more, but did not really want to, and when asked how much, said they did not know.

The differences among leaders and resident location categories have not been discussed so far under policy issues, since they usually have been small. In general, leaders saw water pollution as less serious and getting better more often than the general public.

Issues in land use policy are many and often complex. We could only deal with a few of these. We chose to focus on preserving farm land and natural areas as opposed to urban growth, plus some related questions specifically on drainage.

The loss of farm land to urban uses is becoming a major policy issue in many areas. Our initial question on this was: "As you know, many areas of farm land are converted to urban uses such as businesses, industries and homes every year. How do you feel about this loss of farm land?" The majority of respondents were concerned about this loss, 28 percent were very concerned, 41 percent were mildly concerned, and 29 percent were not concerned. The concern for prime farm land was as strong with 72 percent seeing a need to explore or develop ways to preserve it. Leaders were somewhat less concerned than the general public in their responses to both of these questions. There was a strong concensus for the "need for parts of the countryside in Tippecanoe County to be kept in a natural state for future generations to appreciate and use," with 88 percent of the respondents saying yes. In contrast to these questions on preserving rural and natural areas, two questions were asked about urban growth. The first asked "One way for cities to grow is by annexation of surrounding housing developments and rural areas. Do you feel these areas should be brought into the city or not?" Responses were fairly evenly split with 32 percent saying yes (either yes, definitely or yes, but only if people outside the city want to be annexed), 40 percent responding that it depends on circumstances and 22 percent indicating no (either no, people should live in the area of their choice or not under any circumstances). The second question was "Growth and jobs often mean new industry in a community. Sometimes this may also mean some air or water pollution. Would you be in favor of allowing an industry to build a factory which would bring new jobs into the county, but which would cause some pollution at the same time?" Again respondents were fairly evenly divided, but this time slightly more were against growth, with 35 percent saying no, 40 percent indicating that it depends and 23 percent responding yes. Leaders were somewhat more in favor of urban growth on both of these questions than the general public.

This series of land use policy questions poses three alternatives which are not entirely compatible with each other, preserving farm land, preserving natural areas and favoring urban growth. The incompatibility of the answers can be seen in the high percentages who favor preservation of farm land and natural areas, and yet only a comparatively small percent oppose annexation. Such data are frustrating to efficient decision making, and therefore might be rejected. However, they may be viewed as representing the complex and contrasting values of a community, which need to be considered for the implementation of natural resources decisions. The multiple interests of persons may make it difficult to have a consistent set of values or attitudes across all topics.

The most specific questions in this study were about drainage, including experience with drainage problems, two types of drainage systems and related policy issues. As indicated above flooding or wet basements had been experienced at some time by about half of all respondents, more than any of the other water problems. They were also asked: "After a heavy rain are there places around here where water stands for some time before it drains away?" The majority, 60 percent said no. Those who said yes, water did stand after a heavy rain, were asked if this was a serious problem. Nine percent (of all respondents) indicated this was not a problem, 22 percent said it was a minor problem and 9 percent stated it was a major problem in their neighborhood. Rural residents were somewhat more likely to report standing water as a minor problem, however, this was clearly a problem for some residents in all areas.

The two drainage systems we wanted to know about were retention basins and open ditches. There are a few retention basins in the study area, and open ditches are common in the rural areas of the state. However, most of the respondents were urban residents, and therefore we chose to introduce this set of questions with this statement:

> When very heavy rains occur in urban areas there is often flooding in streets or peoples' yards. There are a number of ways that this runoff water can be controlled or moved out of the area. The usual way in cities is through underground pipes. Additional ways include retention basins and open ditches.

Respondents were then asked if they had ever lived in an area where retention basins were used. Retention basins were defined for respondents as "usually low, grassy areas, which hold water for a few hours after a fairly heavy rain, and dry out as the water drains away." Nine out of ten persons said they had never lived in an area where they were used. Of the few who said they had, the majority (9 of 15) were leaders. This did not keep most respondents from having opinions about them, however, This was particularly characteristic ofleaders, with the general public more likely to indicate they did not know much about them. Many saw problems associated with proper design, construction and maintenance. Others were concerned about mosquitos and safety for children.

More persons had lived in areas where open ditches were used, but still two out of three said they had not. They also had more comments about them, including whether they work satisfactorily. Although some felt they work alright, many viewed them with qualifications or saw problems. These two statements, one by a leader and one by a general public respondent are representative of this perspective: "It depends on population density, o.k. for suburbs or rural areas, but not for urban areas" and "(They work alright) if there's enough fall, or if not-mosquito breeding, dangerous to little kids."

It is important to emphasize the structure of questions used here. The first two questions were: (1) Have you ever lived in an area where retention basins were used for drainage? (2) Do you know anything about them? Do they work alright, or are there problems with them for people living near them? The same questions were then asked for open ditches. In both cases the majority said no to the first question, but had comments about problems or potential problems on the second questions. A third question was addressed to "How would you feel about living near a retention basin?," ... near an open ditch?" The level of concern expressed in response to these questions was greater, than to the preceding question, particularly for the general public. For retention basins, 36 percent expressed no concern, 37 percent were a "little concerned" and 24 percent were "quite or very concerned." The comparable figures for open ditches were 35, 31 and 33 percents respectively. Mosquitos and other health and safety reasons were frequently given as the reasons for concern.

Rural residents were the least concerned about either drainage method, perhaps reflecting greater familiarity with open ditches and farm ponds as similar to retention basins. Transition area residents were the most concerned about both methods. They live in the area undergoing the most rapid land use change, by definition. Thus, they may be more likely than urban residents to feel these drainage systems could be used in future developments in their neighborhood. This points to one of the most difficult issues in the policy decision making process. Who should participate in the process? Should it be only those people most directly effected, e.g., transition area residents, or all residents, including urban and rural? The answer is a separate policy issue outside of the scope of this study. However, in terms of a data base for input into such decisions, sources of variation (such as location of residence or past experience) should be included rather than presenting only overall or univariate data (such as the percent favoring a particular design).

This section was concluded with two questions on land use policy in relation to drainage. The first was a general question that asked "Who should be responsible for seeing that adequate drainage exists in an area, individual property owners, the developer, local, state or federal government?" The developer and state government were both named by about 60 percent of the respondents. This varied from about 50 to 67 percent among the respondent categories, with two exceptions. Eighty-nine percent of leaders thought local government should be responsible, but only 26 percent of rural residents thought it should - they predominantly felt developers should be. Only 23 percent felt property owners, 22 percent said state government and 12 percent answered that federal government should be responsible. There was no significant difference between those who had and had not experienced flooding or wet basements in whom they felt should be responsible for adequate drainage, nor between those who had and had not experienced sewers backing up.

Then, a more specific policy issue was raised. "One way to deal with this problem (of poor drainage) is to have a firm policy to prevent people from building in wetlands -- areas that are low or poorly drained, and frequently have water standing in them. Would you be in favor of or opposed to such a firm land use policy?" The majority of respondents favored such a policy. There was substantial variation among groups, however, with 78 percent of the leaders, 68 percent transition residents, 48 percent urban and 47 percent rural residents being very or somewhat in favor of such a policy. Only 7 percent were very opposed and 15 percent somewhat opposed, with the remainder uncertain. Again, experience with a flood or wet basement, or sewers backed up, was not related to position on this land use policy. When asked why they took the position they did, leaders had many more reasons than the general public. Besides recognizing the undesirable and potentially unhealthy living conditions, leaders were more aware of potential future problems, and the resulting expectation for governmental assistance. As one said "Because the developer wouldn't be tempted to build and walk away leaving local government stuck with an expensive problem." In contrast to this awareness of the complexities resulting from developing such areas were the views that "the land can be drained" and "its the property owners land" to use as he/she wishes, most often expressed by the general public.

The most important points to note in summarizing this section are that although most people had not lived near either retention basins or open ditches, there were many concerns about them. This position, plus the fact that a majority favored a land use policy preventing building in wetlands, suggests that such policy approaches should be given serious consideration as an alternative to such "open" drainage systems. Additionally, if such a policy were to be developed at the local, rather than state or federal level, it would be more acceptable.

C. *Public Involvement*

The last several years has seen a substantial increase in citizen participation in natural resources decision making. This has been incorporated in law for many programs. Participation takes many forms, and undoubtedly varies considerably in effectiveness in terms of communicating a point of view. The objective here was to learn something about how citizens see their role with regard to the kinds of issues we have been addressing.

After the various water resources issue questions had been asked, respondents were asked the following:

> Now I'd like to ask a question about how water resources decisions are made. Some people say that ordinary citizens should be involved in making these decisions, while others say that water technology is so complicated that is should be left up to the experts, or to elected officials. In your opinion should citizens be involved in such decisions?

The great majority of respondents, 76 percent, thought citizens should be involved. Rural residents and leaders particularly thought they should be, 90 percent and 85 percent, respectively. Earlier, when we had asked whether there were local environmental problems, we also asked if the respondent was doing anything to help solve the problem. Fourteen percent said they were currently working on solving the problem(s) they had mentioned. Half of these were leaders, who of course, make up only about a fourth of the respondents. Nevertheless, while the numbers are not large, this suggests that a fair number of residents are involved in seeking problem solutions, especially in comparison with the very small numbers of community participants indicated in many studies. This substantial belief in public involvement is not a result of extreme political views. Forty-four percent consider themselves middle-of-the-road, 34 percent say they are conservatives, and 11 percent liberals. Only 6 percent described themselves as very liberal or very conservative. This interest in public issues was supported by how frequently they reported following the accounts of political and governmental activities in the news media: 57 percent daily or almost every day, 19 percent often, or several times a week, 17 percent occasionally and only 7 percent never or almost never.

These data suggest that respondents believe in public involvement, and that a fair number practice it. They also make an effort to be involved. There may be a social desirability affect here, that is, "people should be involved, so that's what I'll tell the interviewer." Independently from this study, however, a number of local issues in the study area have had substantial public involvement in recent years, which provides some evidence for the validity of these data.

10.4 Predictions on Policy Issues and Participation

The first concern here is whether a set of variables have been identified that would predict a person's stand on a given policy issue. It was shown earlier that leaders were very likely to favor a firm policy to prevent building in wetlands, while only about half of the urban and rural residents favored such a policy. The research question is whether a set of variables used in combination can do a more precise job of indicating which persons do or do not favor a particular policy.

To do this we used multiple regression, a statistical technique to find the best possible linear equation to predict each of six policy variables in the study: the seriousness of pollution in Tippecanoe County (hereafter called pollution), how concerned an individual was about retention basins (retention basins), how concerned an individaul was about drainage ditches (ditches), whether or not there should be a firm policy to prevent building in wetlands (wetlands), how concerned people were about the loss of farm land due to its conversion to urban uses (farm land), and lastly, whether or not cities should annex surrounding housing developments and rural areas (annexation). These policy variables are treated as the dependent variables in the analysis.

We chose seven potential explanatory or independent variables to include in the step-wise regression. We used the same seven independent variables in each equation hoping that a pattern of variables might emerge helping us to explain environmental attitudes generally. Originally the list of independent variables was larger but we chose to narrow the list by excluding one of each pair of variables that were highly correlated with one another. The seven variables we finally chose to work with were: where a respondent lived, i.e., urban, transitional or rural residency (X_1), whether the respondent had experienced one or more selected water-related problems (X_2), respondent's age (X_3), sex (X_4) and annual income (X_5), how many places outside Tippecanoe County that the respondent had lived for at least one year (X_6) and lastly a measure of how often the respondent talked about political or community issues with his or her relatives, friends or neighbors (X_7). We felt that these independent variables tapped different aspects of a person's socail and demographic characteristics. We also felt that these variables would be more accessible and useful to decision makers than variables which tapped more attitudinal dimensions of an individual.

Separate equations were developed for leaders and nonleaders on the assumption that these two groups had different if not contrasting characteristics. Additionally, the two samples were collected differently as noted earlier and it would be inappropriate to combine them here.

The data for leadres and nonleaders show first that the amount of variance explained in the policy variables by any one equation is quite small. R^2 was less than .50 in all but one equation when it was .52. Secondly, the tables show that there is no pattern to the order in which the independent variables entered the regression equations to explain the policy variables.

We also used stepwise multiple regression in order to try to explain who participates most often. The importance of this analysis stems from the frequent finding that certain groups participate more extensively than others in activities that are intended to affect policy outcomes. Our measure of participation for each respondent was the number of participation activities on the list of 18 which the respondent said he or she had done. We chose ten independent variables to comprise our initial predictor list. They were: the residential location of each respondent, i.e., whether they live in urban, transitional or rural areas, (X_{11}); whether the respondent is a leader or nonleader (X_{12}); the age (X_{13}), sex (X_{14}) and annual income (X_{15}) of the respondent; the number of places outside Tippecanoe County where the respondent lived for more than one year (X_{16}); how often (never, occasionally, often, daily) the respondent followed accounts of political and governmental activities in the news media (X_{17}); how concerned about community problems is a respondent (X_{18}), (this variable was created by summing the number of community problems -- environmental quality, poverty and educational problems -- a respondent said he or she was "somewhat" or "very" concerned about); whether the respondent was employed at a full-time job or not (X_{19}); and, finally, whether a respondent was very liberal, liberal, middle-of-the-road, conservative or very conservative (X_{20}).

Table 10.2 presents the results of the multiple regression of participation on the selected independent variables over all respondents. If we were to use the criterion that individual variable significance be less than .05 when it enters the equation, we find that the first four variables to enter the equation meet this criterion. Thus, respondents who have higher participation scores than other respondents are likely to be leaders rather than nonleaders, have higher incomes than other respondents, to follow accounts of political and governmental activities in the news media more often and express concern for a variety of community issues. These four variables (X_2, X_5, X_7, X_8) alone explain about 50 percent of the variance in the participation scores. The other variables add little to this.

Table 10.2 Summary of Multiple Regression of Participation on Ten Independent Variables for All Respondents

Independent Variables*	Beta	Multiple R	R^2	Independent Variable Significance	Multiple R Significance
X_{12}	.30	.59	.35	.000	.000
X_{15}	.27	.66	.43	.000	.000
X_{17}	.19	.69	.47	.001	.000
X_{18}	.17	.71	.50	.006	.000
X_{11}	-.11	.71	.51	.071	.000
X_{13}	-.09	.72	.51	.310	.000
X_{19}	.08	.72	.52	.295	.000
X_{14}	.08	.72	.52	.297	.000
X_{16}	.06	.72	.52	.328	.000
X_{20}	-.07	.72	.52	.906	.000

**See text for complete description of variables.*

Table 10.3 presents a summary of the regression of the participation variables on nine of the independent variables for nonleaders. The variable measuring whether a respondent is a leader or nonleader is excluded because we only are looking at nonleaders in this table. We find that the first three variables to enter the regression equation meet the .05 criterion. It appears that the higher the participation scores, the more likely a nonleader has a higher income than the other respondents, follows accounts of political and governmental activities in the news media more often than the other respondents and expresses some or much concern more often for a variety of community problems. These three variables (X_5, X_7, X_8) explain twenty-eight percent of the variance in the participation scores.

Table 10.3 Summary Table of Multiple Regression of Participation on Nine Independent Variables for Nonleaders Only

Independent Variables*	Beta	Multiple R	R^2	Independent Variable Significance	Multiple R Significance
X_{15}	.30	.42	.18	.000	.000
X_{17}	.22	.49	.24	.003	.000
X_{18}	.19	.53	.28	.020	.000
X_{16}	.16	.54	.29	.156	.000
X_{13}	-.15	.55	.31	.113	.000
X_{14}	.19	.57	.32	.140	.000
X_{19}	.15	.58	.34	.118	.000
X_{11}	-.11	.59	.35	.182	.000
X_{20}	.04	.59	.35	.604	.000

**See text for complete description of variables.*

Table 10.4 presents the same sort of summary information but for leaders only. If the criterion that the individual variable significance be less than .05 in order for a variable to be considered as making a statistically significant contribution to the regression equation we find that no variables enter statistically significantly. As with the policy variables above, we choose to ignore this criterion for leaders since they are essentially a population rather than a sample. The lack of significance is in part attributable to the smaller number of cases among leaders. Therefore, it is worthy of note that the first two variables to enter the equation were how often the leader followed accounts of political and governmental activities in the news media and expressed concern for social issues. Income did not enter the equations again apparently because of its low variance among leaders.

Table 10.4 Summary Table of the Multiple Regression of Participation on Nine Independent Variables for Leaders Only

Independent Variables*	Beta	Multiple R	R^2	Independent Variable Significance	Multiple R Significance
X_{17}	.29	.26	.07	.100	.100
X_{18}	.39	.35	.12	.138	.086
X_{20}	-.28	.41	.17	.172	.081
X_{11}	-.10	.44	.20	.245	.090
X_{13}	.21	.46	.21	.366	.117
X_{19}	-.16	.48	.23	.409	.152
X_{16}	-.47	.48	.23	.769	.228

**See text for complete description of variables.*

These data show a consistent pattern in which leaders, higher income persons, those who follow news media accounts of governmental activities and who are concerned about more community issues participate more than others in a variety of activities from voting to signing petitions in order to influence the outcome of political events. It is these people who participate more whose views often are more likely to be taken into account in policy decision making. As shown earlier in the discussion on policy issues, the views of leaders and nonleaders (the most important of these variables for predicting participation) were often similar. This was generally true with regard to water pollution, preserving parts of the countryside and concern about drainage systems. However, on other issues such as concern about loss of farm land, conserving prime farm land, annexation, responsibility for drainage and a firm wetlands policy differences were greater between leaders and nonleaders, and in some cases they were substantial.

The views of those who participate less are less likely to be obtained through the usual participation processes. If their views are to be considered in formulating public policy, it appears that techniques which deliberately seek them out, such as the survey method does, would need to be used.

10.5 Summary and Conclusions

An important aspect of learning what knowledge and attitudes people have about a topic is how we ask questions. In a profound sense, our questions tell the listener what we are interested in knowing about. They are a stimulus for an answer. The implications of this can be seen in three questions of increasing specificity in this study. (1) What would you say is the most serious problem facing this community right now? (2) Do you think there are any problems with the environment in this area, now or in the last few years? (3) We hear a good deal of talk about the problem of pollution in the United States, including water pollution. How serious do you think water pollution is in Tippecanoe County? The data show that the more specific the question, the higher the percentage who think there is a problem, at least to some degree.

Which is the right answer? How serious do people think (water) pollution is? The answer will not be a constant, now and forever. It will vary with the structure of the question, and the information people have on levels of pollution. An approach for the researcher or the planner is to seek data about the issue in multiple ways. For example, different but related questions can be asked, as above. Questions (2) and (3) were much more alike in their responses, than they were compared to question (1) which was very unstructured and very open-ended. Open-ended questions that allow respondents to describe their attitude in more detail can also be very valuable. It seems reasonable to conclude here that there is a moderate degree of concern with the environment and water pollution in particular in the study area, based on these data.

Part of the objective for these data was to compare leaders and the general public on how they saw selected water policy issues. On many questions the differences were small. However, the importance of such comparisons is accentuated by findings that might not be expected. Leaders were somewhat more likely to identify themselves as conservatives politically, and yet their positions, collectively, were less conservative than the general public on two issues: (1) they were willing to pay more in tax dollars to combat water pollution, and (2) they were more in favor of a firm policy to prevent building in wetlands. As an additional illustration of such sub-group comparisons, it was the rural and urban residents who were least favorable to such a wetlands policy.

The importance residents place on local government as opposed to state or federal government is seen in several ways. They disagreed strongly with the statement that "water pollution is the federal government's problem." They felt it is local government and developers, who are responsible for seeing that adequate drainage exists. And when asked who is responsible for decisions about water prices and quality, they were much more likely to name some local entity rather than a state agency.

The final point is about the relationship of experience to a feeling of concern. It was not necessary for respondents to have direct experience with either retention basins or open ditches for respondents to have concern about them. The use of open-ended questions in combination with structured questions provided useful data here. This indicated the kinds of concerns people had, including the need for careful design and construction, plus maintenance, in addition to mosquitos and safety. Proposals for use of these types of drainage systems could take these factors into account, and recognize whatever additional costs and problems might be involved to satisfy these concerns. The strong belief in citizen participation expressed by these respondents suggests a potential for their involvement in such decisions. This might be deliberately sought in the very early stages of planning, or it could be omitted to await their reactions to plans already developed.

The analysis of differences in positions on the policy issues up to this point considered leadership and place of residence primarily, and socioeconomic status to some extent. Are additional variables that describe a person's social structural position in a community useful for estimating his/her position on these policy issues? To answer this question, seven independent variables (location of residence, experience with water problems, age, sex, income, number of places lived outside of Tippecanoe County, and how frequently they talked about political and community issues) were used. The method was a step-wise multiple regression, done separately for leaders and for nonleaders and for each of six policy variables. The results of this analysis showed that these particular independent variables did not account for a large portion of the variance in any of the policy variables, and that there was no predominant pattern among these variables in the order in which they entered the regression equation.

Another important part of the policy decision making process is who participates in it. Those people who participate little or not at all in the activities examined are likely to have little impact on policy decisions. Again, step-wise multiple regression was used. This showed that leaders, those with higher incomes, who follow news media accounts of governmental activities and are more concerned about community issues participate more.

In conclusion, this study illustrates some important points about the use of survey research in urban water resources policy studies. It showed that the general, open-ended "most important community problem" type of question produced fewer indications of concern with water resources issues than more specific questions. The more detailed questions provided more specific information about which issues people were and were not concerned about. Additionally, leadership and place of residence provided information on who expressed concern with which issues. However, the more detailed regression analysis did not show any consistent pattern among a set of variables as predictors of position on six policy issues. A number of possible reasons for this are given earlier. Regardless, it seems to indicate that there is no simple set pattern of response across issues by leaders, or urban, transitional or rural area residents on these issues. In contrast, there is a quite distinct pattern to political participation, which is positively related to leadership, income, attention to news media, and concern for community issues. Given these findings, the social survey appears to be a useful means of determining the extent to which there is consensus or lack of consensus on issues, and can be an especially useful source of information to policy makers when the views of the more active members of a community differ from those of less active members.

Chapter 11

Aesthetic Qualities of Urban Land and Water Resources of Tippecanoe County, Indiana

11.1 INTRODUCTION

Scenery is a natural resource that is an asset to the landscape in which it is found. Like all resources, scenery is only a potential resource asset, and does not become an actual asset until recognized, valued and utilized by a society with a particular level of cultural and economic development. Therefore, the objective of this study is to evaluate the scenic resources of Tippecanoe County for the purpose of identifying areas of unusual beauty, particularly water-related scenes, which may merit protection during future growth of urban areas.

The specific operational framework within which this investigation has been conducted is as follows:

1. Identification of environmental elements that control scenic quality, and which can be evaluated with a minimum amount of subjectivity.
2. Definition of environmental entities that enhance scenic quality, and entities which inherently are contrary to scenic beauty of landscapes.
3. Comparison of landscapes with different physical, cultural, and biologic characteristics in order to identify those landscapes which are commonplace and those landscapes that are unique with respect to the scenic elements under consideration.
4. Definition and utilization of relative aesthetic indices, to hierarchically rank landscapes by scenic value based on analyses of the environmental elements which control secnic beauty.

The following concepts provide a philosophical framework for this investigation into scenic aspects of landscapes:

1. Scenery is a natural resource that can be developed, managed and conserved by rational, objective planning for present and future use.
2. Scenic resources are continuous across the surface of the land.
3. Like soils, scenic resources vary in quality from place to place.
4. Scenic resources are visual amenities that can be evaluated in terms of an aesthetic judgement based on the perception of tangible and intangible elements of the environment.
5. Physical, biologic and cultural characteristics collectively control scenic quality of landscapes.
6. Landscapes with unique physical, cultural and biologic characteristics are more significant to society as scenic resources than everyday or common landscapes.
7. Topographic relief, presence and abundance of surface water, and diversity of surface form are the most aesthetically pertinent physical aspects of the landscape.
8. Naturalness, distribution and diversity of floral communities are the most important biologic aspects of landscape scenery.
9. Man's contribution to scenic quality in the landscape is manifested in his utility of the land.
10. Personal judgements of aesthetically displeasing aspects of the environment are more universally consistent than judgements about beauty in the environment.

Physical scenic factors are those components of the landscape which determine its geomorphic character and expression. One of the most tangible physical elements of landscape is the presence and abundance of surface water. In fact, many recent studies of scenic resources have concentrated on surface water, particularly the riverine environment. These studies concluded that scenic quality in a landscape increases as the abundance and diversity of surface water increases. Surface water characteristics that most pertinent in developing a set of scenic standards are: 1) drainage density, 2) drainage frequency, 3) drainage order,

4) drainage pattern, 5) drainage texture, 6) number and size of lakes, and 7) number and size of swamps.

Previous studies also tend to agreement that agricultural and forest land uses are neutral or somewhat positive aesthetic elements of the cultural environment. Industrial, commercial and residential land use practices normally are considered antithetical to scenic beauty, in decreasing order as listed. It is, however, difficult to arbitrarily rank land use practices on an absolute hierarchical scale of aesthetic quality because there are very few numerically-based experiments in assessment of landscape quality.

11.2 General Methodology

Fifty discrete landscape units were delineated in Tippecanoe County (Fig. 11.1). These landscapes were defined and separated on the basis of surface morphology and cultural use of the land. Areas of similar relief, landform characterization, elevation, and land use constitute discrete landscapes. Landscape mapping was accomplished by analyzing U.S.G.S. 7½-minute and 15-minute scale topographic maps, low altitude black-and-white air photos (scale 1:20,000), and high altitude NASA color infrared photography (scale 1:100,000). Geological, soils, and drainage maps are also useful.

Physical, biological and cultural elements of landscapes pertinent to scenic assessment are shown in Table 11.1. "Evaluation categories" were assigned to all "descriptive factors" in each landscape. The total range of each evaluation category was established by observation of the maximum variation of each descriptive factor in the study area. The range of each evaluation category is of pragmatic necessity, somewhat arbitrary and subjective. Descriptive factors and evaluation categories used were "tuned" for use in the Tipton Till Plain physiographic subprovince. Adjustments in these criteria are necessary if this technique is applied to different physiographic provinces or subprovinces.

A total of 400 field stations, 8 per landscape, were used as field observation sites. Station locations were randomly chosen on topographic maps before entering the field; this circumvents investigator bias and insures that a major portion of every landscape will be directly observed. Other compensations to diminish observer bias included use of multiple evaluations on each field excursion, and a limit of 4 hours per day of viewing so as to minimize observer fatigue and ennui.

11.3 Computation of Indices

The matrix and factor analysis technique of Leopold (1969) was used, in a modified form, to quantitatively evaluate scenic factors of riverscapes. Table 11.1 is a matrix in which each descriptive factor defines a row and each evaluation category delimits a column. Any position on the matrix can be defined as $x_{i,j}$, where i is the descriptive factor number (1-37) and j is the evaluation category numbers (1-5) as shown below (Melhorn et al., 1974).

$$\begin{array}{cccccc} & j \longrightarrow & & & & \\ & x_{1,1} & x_{1,2} & x_{1,3} & x_{1,4} & x_{1,5} \\ i & x_{2,1} & x_{2,2} & x_{2,3} & \ldots\ \text{etc}\ldots & \\ \downarrow & x_{3,1} & x_{3,2} & \ldots\ldots\ \text{etc}\ \ldots & & \\ & x_{31,1} & x_{31,2} & x_{31,3} & x_{31,4} & x_{31,5} \end{array}$$

Leopold (1969) defined "Uniqueness Ratio" (UR) as the reciprocal of the number of landscapes sharing the same evaluation category in any given descriptive factor. For example, if ten landscapes all contain abundant, low relief hills (factor 1, category 1) then the UR for all landscapes for this factor is 1/10 or 0.1. However, if a given landscape "A" is characterized by isolated high relief hills (factor 1, category 4), then its UR is 1/1 or 1.0 and the other nine landscapes have UR's of 1/9 or .111. Thus, for this descriptive factor landscape "A" is unique among all landscapes considered. Of course, 1.0 is the maximum UR for any given factor. In computation of Uniqueness Ratios the number (1-5) given each evaluation category has no good or bad connotation - category 1 of factor 25 is no better or worse aesthetically than category 5 of the same factor. Each descriptive factor is given equal weighting in the computation of UR's. Total uniqueness is the sum of the UR's within each physical, biologic or cultural group for each landscape.

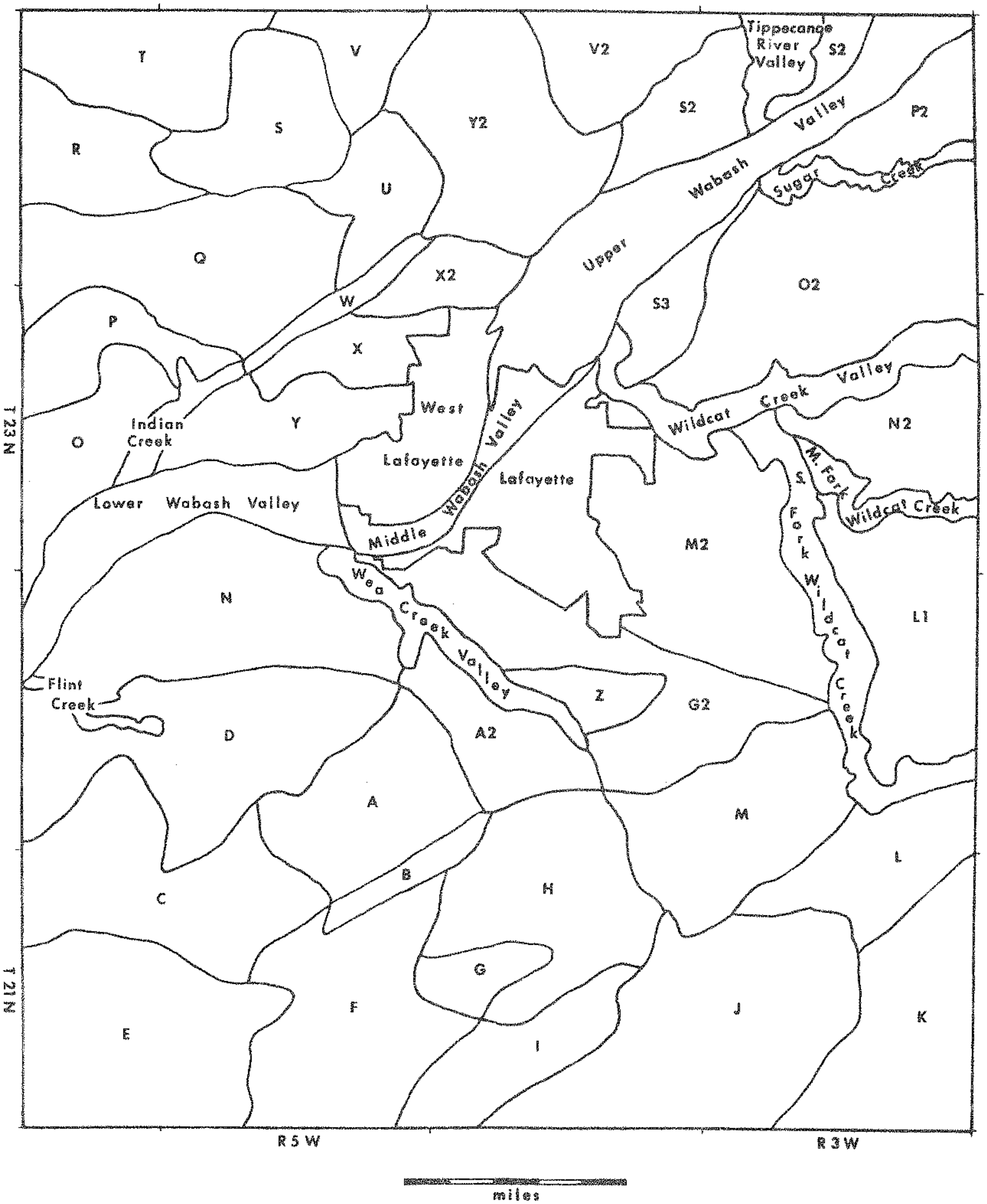


Figure 11.1 Landscapes Aesthetically Evaluated in Tippecanoe County

Table 11.1 Factors of Landscape Aesthetics

DESCRIPTIVE CATEGORY	EVALUATION CATEGORY				
	(1)	(2)	(3)	(4)	(5)
Physical Factors					
1) Convex landforms	Abundant low relief hills	Isolated low relief hills	Abundant high reflief hills	Isolated high relief hills	Insignificant
2) Concave landforms	Abundant shallow valleys	Isolated shallow valleys	Abundant deep valleys	Isolated deep valleys	"
3) Dominant landform type	Ground moraine	Ridge moraine	Outwash plain	Floodplain	Complex
4) Landform diversity	Simple (1)	Moderately		Moderately	Complex > (3)
5) Landform Distribution	Concentrated in 1 area	Concentrated in scattered areas		Partially disseminated	Equally disseminated
6) Landscape discontinuities	Many sharp	Few sharp	Many gradual	Few gradual	
7) Floodplain development	Narrow	Moderately narrow		Moderately wide	Wide
8) Total relief	0-65	66-95	96-135	136-190	> 190
9) Local relief	20	20-35	36-60	61-85	> 85
10) Ground slope	0-2	2.1-6	6.1-11	11.1-14	> 14
11) Contour frequency	7	7-12	13-20	21-29	> 29
12) Panorama	completely unobstructed	predominantly unobstructed	Median	predominantly obstructed	completely obstructed
13) Drainage density	0-4.5	4.6-7	7.1-9	9.1-13	> 13
14) Drainage frequency	20	21-30	31-38	39-45	> 45
15) Drainage order	2	3	4	5	> 5
16) Drainage pattern	dendritic	trellis	parallel	deranged	complex
17) Drainage texture	fine	moderately fine	medium	moderately coarse	coarse
18) Number of lakes	0-1	2-3	4-5	6-9	> 9
19) Lake distribution	Concentrated in 1 area	Concentrated in scattered areas	None	Partially disseminated	Equally disseminated
20) Number of swamps, bogs	0-1	2	3	4	> 4
21) Distribution of swamps	Concentrated in 1 area	Concentrated in scattered areas	None	Partially disseminated	Equally disseminated
Biological Factors					
22) % area covered with indigenous vegetation	0-10	11-17	18-25	25-45	> 45
23) Dominant floral type community	Grass, shrubs	Occasional patches of trees	Predominantly ornamental	Predominantly forests	Occasional trees
24) Floral type diversity	Few		Many		Abundant
25) Ornamental genera	None	Few		Many	Abundant
Cultural Factors					
Land Use (% total area)					
26) Agricultural	0-50	51-61	62-72	73-89	> 89
27) Residential	0-3	3-4	5-7	8-15	> 15
28) Commercial	0-1	2-3	4-5	6-10	> 10
29) Industrial	1	1-2	3-4	5-7	> 7
30) Forest, Shrubland	0-10	11-17	18-25	25-45	> 45
Other					
31) Misfits	0	1	2	3	> 3
32) Quarries, pits	0	1	2	3	> 3
33) Road, railroads	very infrequent	occasional	frequent	abundant	very dense
34) Building density	"	"	"	"	"
35) Structures	none	"	"	"	very abundant
36) Population density	very sparse	sparse	moderate	dense	very dense
37) Historical, archeological sites	none	1	2	3	> 3

The objective of computing Uniqueness Ratios is to determine how closely a landscape approaches a state of uniqueness relative to other landscapes. We realize that in the correct semantic usage, the state of being unique is absolute with no qualification of degree. However, we believe that utilization of Unieuqness Ratios to compare aesthetic elements between landscapes is the most objective approach yet devised for scenic resource evaluation.

The Uniqueness Index (UI) was defined by Melhorn et al. (1974) as "the percentage of total possible uniqueness" in an evaluation of scenic riverscapes. The UI gives each descriptive group (physical, cultural, and biologic) equal weighting in addition to the equal weighting applied to each factor in the computation of UR's. This is necessary because the descriptive groups contain unequal numbers of descriptive factors. Each descriptive group UR subtotal is divided by the number of descriptive factors in that group. The UI is placed on a convenient scale of 1000 by multiplying each of the three descriptive group subtotals by 333.3. For example, if for the 21 physical descriptive factors a landscape received 14 of a possible 21 points, then the UI group is $14/21 \times 333.3 = 22.2$. This computation is done for each Descriptive Group for all landscapes. The UI subtotals are then summed to give a UI total for each landscape.

The Aesthetic Index (AI) is described as a measure of what constitutes beauty or ugliness in landscape. The AI is calculated by the equation $AI = UI_{total}(1-X/Y)$, where X = total UR value, zeroed at $X_{i,j}$ positions contrary to scenic beauty, and Y = total UR values of $X_{i,j}$ positions of the matrix that could possibly have been zeroed. Calculation of AI then is determined in the same way that UI is determined.

Figure 11.2 is a hypothetical computation of Uniqueness and Aesthetic Indices for two landscapes. The UI's (Fig. 11.2, Table B) indicate that landscape A is unique in more scenic factors than landscape B. However, landscape A has relatively high UR values for factors 1 and 2 which are antithetical to scenic beauty (Fig. 11.2, Table C and A), whereas landscape B has only one unaesthetic factor (5), with a very low UR. Table d depicts adjusted UR's after "zeroing" evaluation categories considered as negative components of scenery in each landscape. Therefore, landscape B has a much higher AI value than landscape A (Fig. 11.2, Table E). Thus, it is possible for a landscape to have a relatively high Uniqueness Index, but score low on the Aesthetic Index because of the presence of factors considered contrary to scenic quality. However, if a landscape contains no ugly elements, x=0, and AI=UI.

A. *Method of Data Analysis*

An optimal degree of discrimination between "unique" and "commonplace" factors of landscape scenery seems possible if a population of 4-7 is utilized in the calculation of Uniqueness Indices (Melhorn et al., 1974, p. 79). For this reason, the 50 Tippecanoe County landscapes were assigned to one of nine "Sections" containing 5-7 landscapes each, in order to compute relative Uniqueness and Aesthetic Indices of each landscape (Fig. 11.3). The nine sections were delineated on the basis of the geographic similarity of their respective landscapes.

Relative UI's and AI's were calculated for each landscape in each section. All computations were machine generated using the LAND Program (Melhorn et al., 1974*). It must be remembered that Uniqueness and Aesthetic Indices are relative and serve only to hierarchically rank the landscapes of each section in order of aesthetic quality according to the evaluated criteria. Scores within each Section may be considered "absolute," but comparison of AI or UI scores between different Sections in meaningless.

A second set of indices is then computed for the set of landscapes which received the highest AI score for each of the nine Sections. This technique allows a hierarchical ranking of the nine most scenic landscapes in Tippecanoe County, as determined from the Aesthetic Indices.

**Melhorn, W. N., et al. 1974, "Landscape Aesthetics Numerically Defined (LAND System): Application to Fluvial Environments," Purdue Univ. Water Resources Tech. Rept. 37, 102 pp.*

A

Descriptive Factor	Evaluation Categories Landscape A	Landscape B
1	4	1
2	4	1
3	2	3
4	1	2
5	5	4

B

Descriptive Factor	Uniqueness Ratios Landscape A	Landscape B
1	.500	.333
2	.333	.333
3	.500	1.000
4	1.000	.250
5	.500	.250
UI	$\frac{2.833}{5}$ (1000)=567	$\frac{2.166}{5}$ (1000)=433

$$UI = \frac{UR_{total}}{5} \times 1000$$

C

Descriptive Factor	Evaluation Categories Anti-thetical to Scenic Beauty
1	3,4,5 ($x_{1,3}$, $x_{1,4}$, $x_{1,5}$)
2	4,5 ($x_{2,4}$, $x_{2,5}$)
3	None
4	None
5	4,5 ($x_{5,4}$, $x_{5,5}$)

D

Descriptive Factor	Adjusted Uniqueness Ratios Landscape A	Landscape B
1*	0	.333
2*	0	.333
3	.500	1.000
4	1.000	.250
5*	.500	0

*Descriptive factors which could have been zeroed

E

Computation of AI	
Landscape A	Landscape B
$AI = UI(1 - \frac{x}{y})$	$AI = UI(1 - \frac{x}{y})$
$x = .500 + .333 = .833$	$x = .250$
$y = .500 + .333 + .500 = 1.333$	$y = .333 + .333 + .250 = .920$
UI = 567	UI = 433
$AI = 567(1 - \frac{.833}{1.333}) = 213$	$AI = 433(1 - \frac{.250}{.920}) = 320$

Figure 11.2 Hypothetical Calculation of Aesthetic and Uniqueness Indices

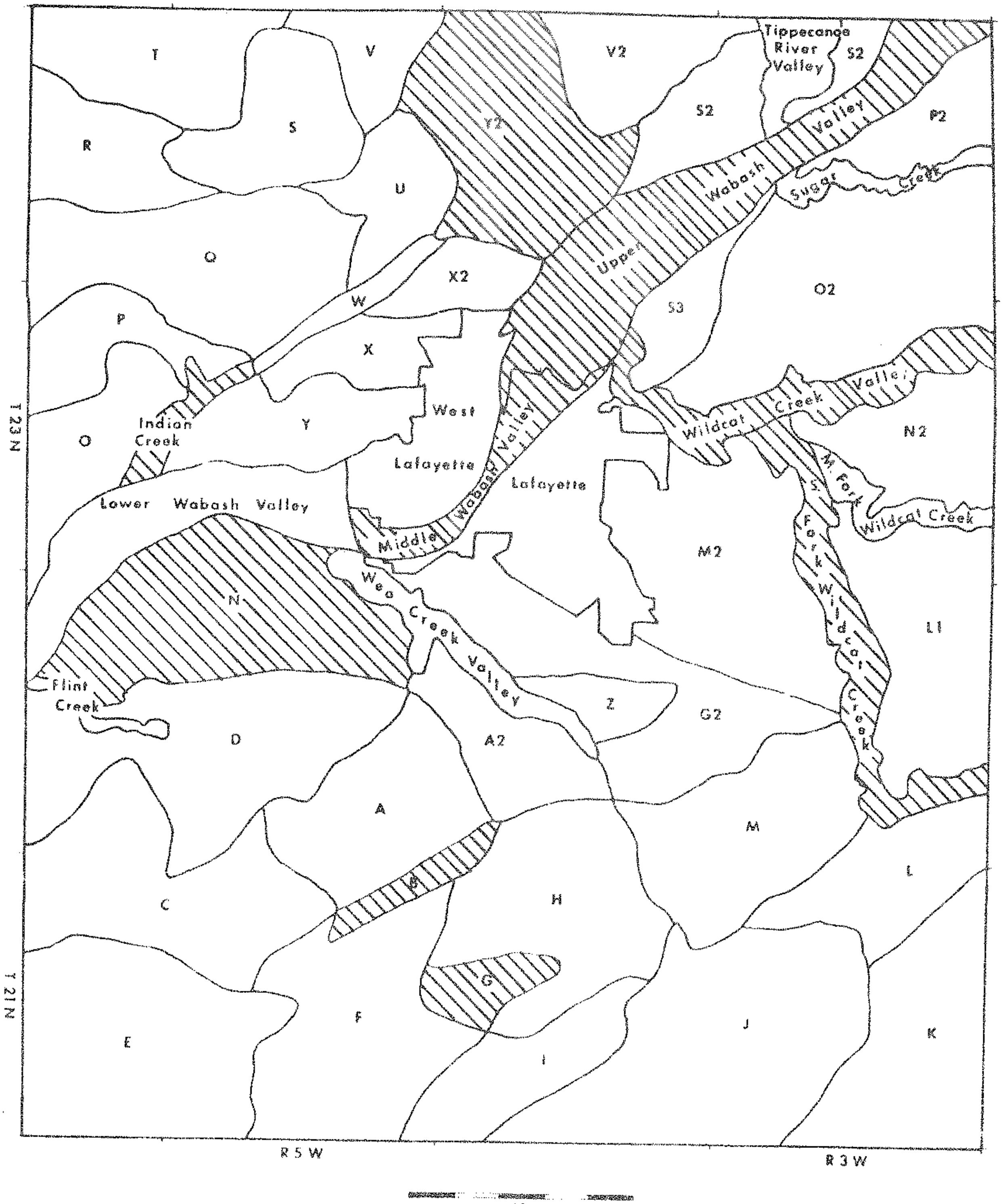


Figure 11.3 Landscapes of Tippecanoe County. The Nine Most Scenic are Shown by the Diagonal Ruling

11.4 Discussion of Results

Of the nine landscapes determined as most scenic in Tippecanoe County, five are stream valleys (Fig. 11.3). Six of the nine sections contain stream valleys; except for one section, a stream is determined as most scenic in each case. Stream valleys are particularly scenic in this region for geologic and cultural reasons. The Tipton Till Plain is characterized by relatively flat ground moraine deposited by continental ice sheets during the Wisconsinian (10,000-80,000 yrs BP) Glacial Stage. The original terrain flatness plus the lack of a well integrated, graded drainage network (owing to the geologic "newness" of the region) makes the Tipton Till Plain a rather featureless surface. Relief is relatively low, major streams are widely spaced and a large portion of the land has been cleared of indigenous vegetation for agricultural purposes. However, streams like the Wabash River have dissected this surface and formed deep and topographically diverse valleys. Steep slopes and high relief along the valley walls of these streams contrasts dramatically with flat, terraced valley floors. In many parts of the valleys native floral and faunal communities are intact. Culturally, the major use of stream valleys is agricultural. Obviously, relative to the interfluve areas, stream valleys in this region have the essential ingredients for unusually aesthetic scenery: 1) high relief; 2) presence of abundant surface water; 3) diversity of topographic form; 4) natural and diverse floral and faunal communities; and 5) relatively little urbanization.

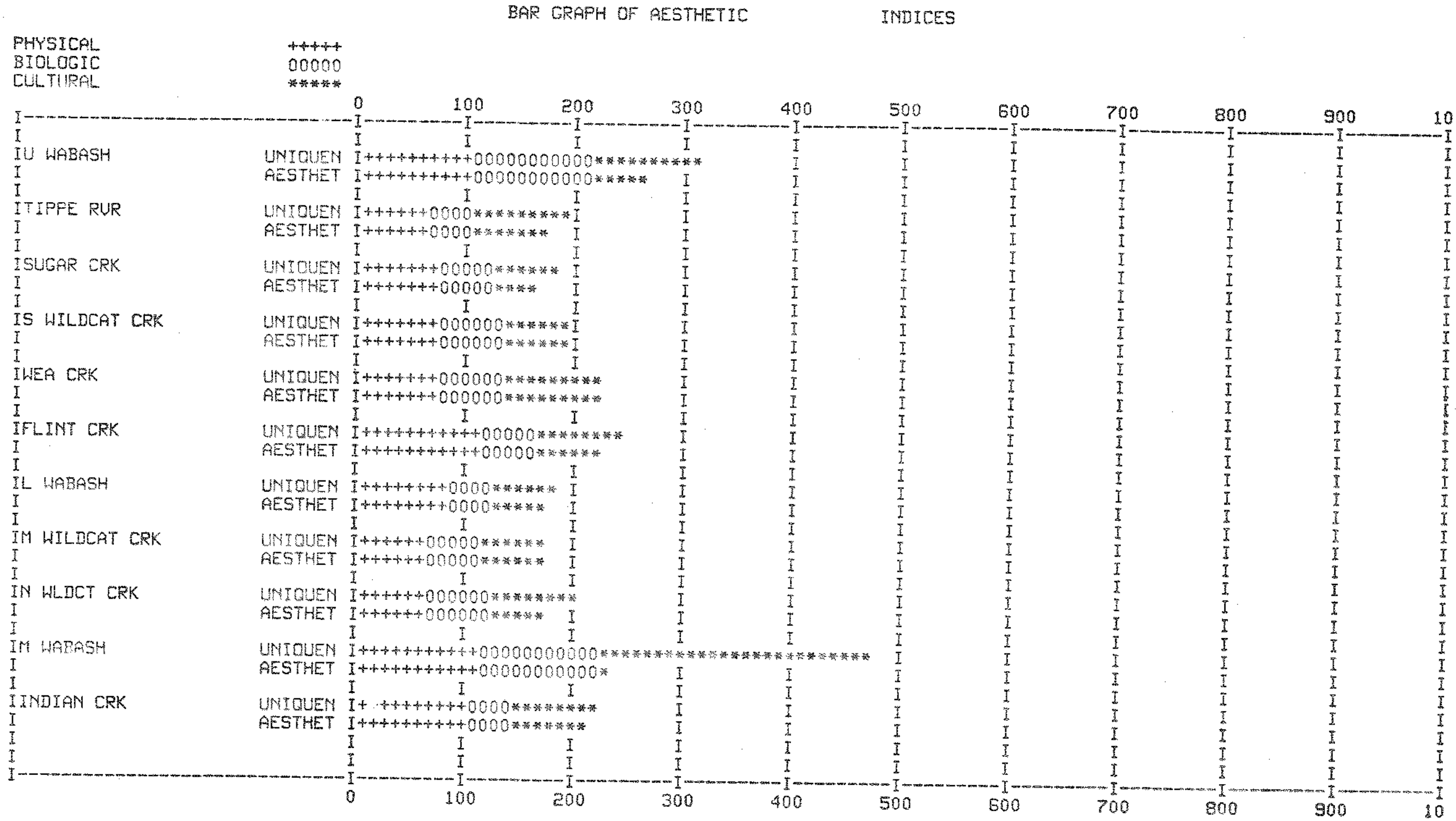
The nine landscapes ranked most scenic in their respective sections were then compared using the LAND data analysis system. UI's and AI's for these landscapes are shown in graph 11.1. Landscape N (see Fig. 11.1) was rated relatively most unique and most aesthetic among these landscapes. The middle Wabash Valley ranked very high in uniqueness but received the lowest AI owing to intense urbanization.

11.5 Aesthetics and Resource Potential of Water Dominated Landscapes

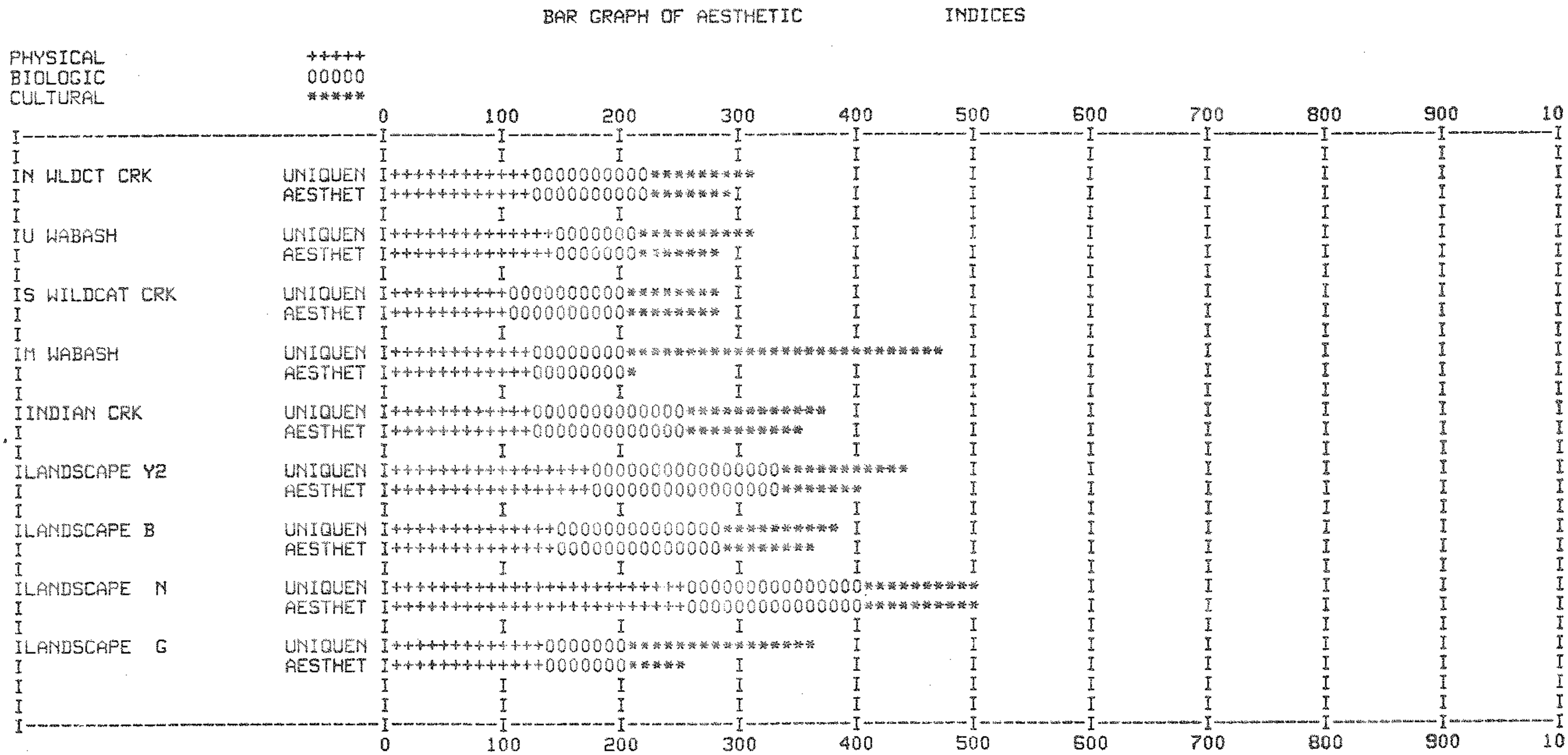
In analysis of landscape aesthetics, five of the nine landscapes in Tippecanoe County rated most scenic are stream valleys. However, eleven major streams in Tippecanoe County were aesthetically ranked using the LAND system. UI's and AI's for these streams are shown on graph 11.2. The middle Wabash River Valley was rated most unique, but ranks second to the Upper Wabash Valley on the Aesthetic Matrix owing to urbanization. Flint Creek, Wea Creek and Indian Creek also rank very high in AI values. Streams most heavily used recreationally (Tippecanoe River and Wildcat Creek) have relatively low AI values.

Lakes are also an important scenic attribute. Although Tippecanoe County has many scenic streams, natural lakes are few. Early settlers drained many natural lakes and ponds to prepare the land for agriculture. Many of the remaining small lakes are now eutrophic or sediment-choked. Lakes support a delicate and unique suite of floral and faunal communities, and in developing communities the presence of scenic lakes greatly increases property values. For these reasons, it is very important to preserve the few natural lakes which exist in Tippecanoe County.

Hadley Lake is the largest lake in the county. It is located on the outskirts of an expanding community, and land development practices detrimental to the integrity of the laked should be avoided. Although lake eutrophication is a natural process, human activity greatly accelerates this process primarily through increased sedimentation and nutrient influx. Since Hadley Lake has no major inlet, sedimentation problems could be minimized if the surrounding area changes from agriculture to urban land use. However, soils surrounding the lake are susceptible to severe erosion. These areas should be protected by vegetative cover during development to prevent large influxes of sediment into the lake. Nutrient enrichment also greatly depletes oxygen in lake waters and makes a lake unsuitable for aquatic life. The aggravated nutrient enrichment of Hadley Lake is presently caused by runoff from surrounding fields treated with fertilizer. Additional homesite development in the area may cause further increase in nutrient enrichment if septic fields are installed. Effluent from septic tanks seeps into the lake by overland flow and through the



Graph 11.1 Indices for Landscapes Determined as Most Scenic in Their Respective Sections



Graph 11.2 Indices for Selected Streams in Tippecanoe County

subsurface. Use of septic tanks should be avoided near the lake and, as development proceeds, the use of lawn fertilizers also should be minimized.

The effects of poor management and planning on small lakes in urbanized areas are exemplified by the Vinton Woods Lakes. These three lakes are in the Vinton Woods residential area of east Lafayette in section 15, R4W, T23N.

Vinton Woods Lakes were constructed in 1954 to enhance property values of the surrounding residential area then planned (Fig. 11.4). The area underwent a construction boom in the early and middle 1960's. Subsequently, the upper lake received great quantities of sediment supplied by the inlet stream from construction sites to the south. In addition, an inadequate sewage treatment facility for another housing development in the upper part of the feeder streams' drainage basin was discharging effluent that eventually found its way to the upper lake. By 1973, the upper lake was reduced to an unsightly marsh by the influx of sediment and nutrients. The other lakes, being downstream in the basin, were less affected. In short, a lake built to enhance property values through aesthetic appeal became an eyesore which detracted greatly from the quality of the surrounding area.

In 1974 the residents of Vinton Woods had the upper lake dredged, at great expense. Also, a sediment catch basin was constructed at the point where the inlet stream enters the lake. In June 1977, we surveyed the upper lake to determine the amount of infilling since 1974. Home construction had continued in the Vinton Woods area and in the Eastwich area in the upper parts of the drainage basin. The sewage treatment facility was discontinued in 1977 when Eastwich was connected to the Lafayette municipal sewage system. Nevertheless, even with the sediment catch basin, the upper lake had lost 15-18% of its volume capacity in three years owing to sedimentation. The water is usually turbid, and trash washed down from the upper basin lines the shore and floats on the surface. In its present condition, the lake has little value to the community and detracts greatly from the scenic quality of the other lakes.

Proper sediment control practices and better advanced planning would have greatly reduced the detrimental effect of construction on this lake. The sediment catch basin probably is too small and too infrequently cleaned to protect the lake from sedimentation. More importantly, proper sediment control practices still are not used at construction sites within the drainage basin.

11.6 Summary and Conclusion

The first step in identifying aesthetic, water-related landscapes is to develop a methodology to identify areas of unusual scenic quality. It is then the responsibility of policy-makers to decide the fate of these scenic resources. Past policy of the Federal government, such as the Wilderness Act of 1964 and the National Environmental Act of 1976, clearly indicates a desire on a national scale to protect and conserve certain areas of outstanding aesthetic quality. Locally, 83% of the residents of Tippecanoe County interviewed in a survey conducted by the Sociology team of this study (see Sociology Section) responded that they believed that land should be zoned for the protection of scenery.

The purposes of this report are: 1) to devise an objective and generally applicable method for evaluating scenic resources of landscapes, and 2) to apply this methodology to identification of landscapes of unusual beauty in Tippecanoe County. Tippecanoe County was divided into 50 different landscapes based on geomorphic and cultural criteria. Physical, cultural and biologic factors germane to landscape scenery were evaluated by the LAND system of data analysis, with the objective of permitting comparisons among landscapes. The concept of uniqueness was retained in a modified form and various indices were computed to hierarchically rank the scenic characteristics of the different landscapes. Nine landscapes in Tippecanoe County were determined as most scenic. Five of these nine landscapes are stream valleys.

In addition, the aesthetic qualities and resource potentials of selected streams and lakes in Tippecanoe County are evaluated quantitatively and qualitatively. Eleven streams were hierarchically ranked in order of scenic quality by using the LAND system. The largest natural lakes in the county were aesthetically evaluated and recommendations are proposed for their future management. The "real-estate lakes" of the Lafayette community were analyzed historically and documentation is presented that bears on their future problems.

11.7 Publications

For further details regarding the aesthetics of land and water resources the reader is referred to the following publication.

PWRRC, Tech. Rept. 110, "Systematic Methodology to Numerically Evaluate Scenic Factors of Landscape: Application to Tippecanoe County, Indiana," by M. C. Gardner and W. N. Melhorn, March 1979.

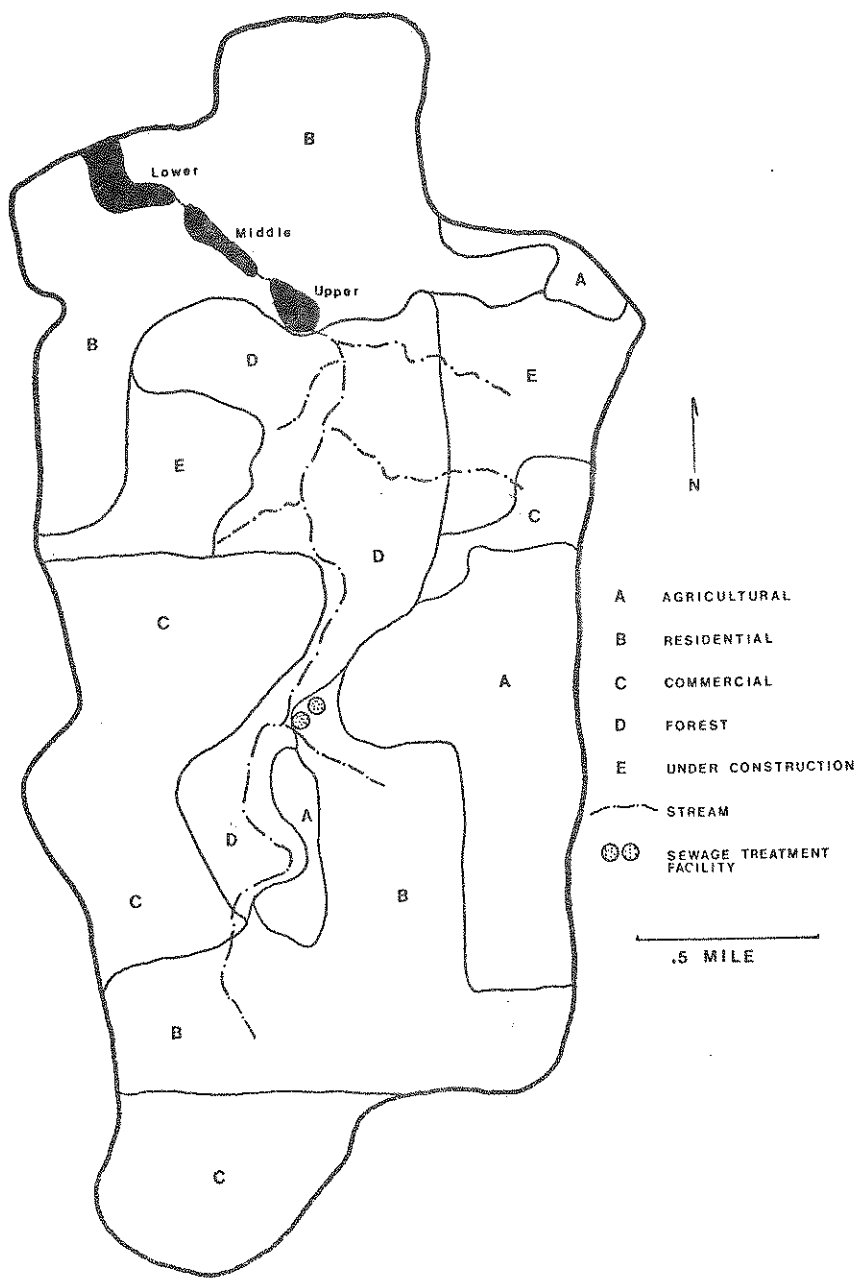


Figure 11.4 Cultural Features of the Vinton Woods Watershed

CHAPTER 12
COMMUNICATION AND IMPLEMENTATION

12.1 Introduction

For the purpose of disseminating the information and of communicating and implementing the methodologies of urban water resources management developed through the project, a combination of a workshop and a short course is proposed.

12.2 Workshop

It is proposed that the workshop be held in the Fall of 1979. It would be a one day meeting in which information would be given on the results of the research. Feedback from the attendance would be expected. The attendance would consist of representatives of federal, state and local agencies and any interested citizens similar to that listed in the final report of Phase I. There would be no charge for attending the workshop. Copies of the final report would be disseminated to the extent of their availability.

12.3 Short Course

This 3-day short course was held on June 3-5, 1979. It covered in detail the principal techniques developed or improved in this research. It included lectures and examples of application. Sets of notes were prepared. Several outside lecturers were invited. There was a fee of $50 to defray the cost of the notes, computer time and course organization. The staff time and honoraria were covered by OWRT.

J. W. Delleur also presented a minicourse entitled "Some Methodologies for Planning Urban Drainage Systems in Small and Medium Size Communities," as part of the International Symposium on Urban Storm Runoff held at the University of Kentucky. This 3-hour minicourse was repeated three times on July 24, 25 and 26, 1979.

URBAN DRAINAGE PLANNING AND DESIGN

Short Course June 4-6, 1979

COURSE FORMAT

The course consisted of three lectures each morning. In the afternoon there was a choice of tabletop calculator or computer oriented sessions in which models and techniques were illustrated.

PROGRAM

Sunday, June 3, 6-9 p.m.

Registration and Notes Pickup, Room 112, Purdue Memorial Union

Monday, June 4, morning - Room 113, Civil Engineering Building

Introduction - D. Wiersma

Introduction to Urban Drainage Design - J. A. Spooner

Design Storm - A. R. Rao

Unit Hydrograph - J. W. Delleur

Monday, June 4, afternoon

Computer Techniques

Illinois Urban Drainage Area Simulator (ILLUDAS) - J. A. Spooner and J. Han

Tabletop Techniques

Design Storm - A. R. Rao
Unit Hydrograph - J. W. Delleur

Monday, June 4, evening

Movie: *Runoff, Land Use and Water Quality*, explores the way land use affects water quality, prepared by Univ. of Wisconsin for EPA.

Tuesday, June 5, morning

Urban Storm Water Runoff (STORM) Model - J. W. Delleur

Urban Runoff Pollution Measurement and Characteristics - J. M. Bell

Economics of Urban Drainage Systems - W. L. Miller

Tuesday, June 5, afternoon

Computer Techniques

STORM - S. A. Dendrou and G. Padmanabhan

Tabletop Techniques

Runoff Quality Estimation - J. M. Bell and W. Melville
Urban Drainage Systems Costs - W. L. Miller

Tuesday, June 5, evening

Banquet
Speaker: William Walker, *Witching Won't Make It So*

Wednesday, June 6, morning

Organic Pollutants in Urban Areas - R. V. Ruhe

Land Use Allocation - S. A. Dendrou

Optimal Planning - K. J. Musselman

Wednesday, June 6, afternoon

Computer Techniques

Optimal Quality of Receiving Waters - K. J. Musselman
Land Use Allocation - S. A. Dendrou and G. V. Loganathan

Tabletop Techniques

Population Projection - M. Marcus
Aesthetics - W. N. Melhorn
Public Acceptance - G. Grossman

Conclusion and Distribution of Certificates

STAFF

J. M. BELL, associate professor of environmental engineering, Purdue University
J. W. DELLEUR, professor of hydraulic engineering, Purdue University
S. A. DENDROU, project engineer, Water Resources Engineers, CDM, Springfield, Virginia
G. GROSSMAN, director, Crisis Center, Lafayette, Indiana
J. HAN, research assistant, Purdue University
G. V. LOGANATHAN, research assistant Purdue University
M. MARCUS, professor, School of Business, Division of Research, Undiana University, Bloomington, Indiana
W. N. MELHORN, professor of geology, Purdue University
W. MELVILLE, Research Assistant, Purdue University
W. L. MILLER, professor of agricultural economics, Purdue University
K. J. MUSSELMAN, A. A. Pritsker and Associates, Lafayette, Indiana
G. PADMANABHAN, research assistant, Purdue University
A. R. RAO, associate professor of civil engineering, Purdue University
R. V. RUHE, Director, Water Resources Research Center, Indiana University, Bloomington, Indiana
J. A. SPOONER, president, Spooner Engineering-North, Oshkosh, Wisconsin
W. H. WALKER, director, Midwest Operations, Geraghty and Miller, Inc., Urbana, Illinois
D. WIERSMA, director, Purdue University Water Resources Research Center

Appendix I
Systematic Planning of Urban Storm-Drainage Facilities

A.1 INTRODUCTION

Work closely related to this research was performed in project OWRT-B-0833-IND entitled "Multilevel Approach of Urban Water Resources Systems Analysis - Application to Medium Size Communities." A very short abstract and a publication list are given here.

A.2 ABSTRACT

A computer program package is developed that integrates and interfaces an urban growth simulation model, LANDUSE, and an urban hydrology model, a modified version of STORM. Alternate growth scenarios can thus be directly related to the corresponding storm-drainage systems. If these systems are designed to achieve specified standards of performance, then a useful comparison among several possible urban growth patterns can be performed. While an urban area encompasses several natural watersheds, the hydrologic models simulate one watershed at a time. The different watersheds that partition an urban agglomeration create a tree-like or dendriform configuration. The planning of a global storm drainage system for such a conglomerate of basins can be efficiently accomplished by coordination of the interactions among the different basins. A model for these interactions is developed. The planning variables are the drainage network capacity, the placement and size of the storage facilities, and the size of a central treatment facility. An example of application is shown for a medium size community in Indiana.

A.3 CONCLUSIONS

This research has emphasized the need to consider an urban watershed in its entirety for purposes of urban storm drainage system planning. This emphasis resulted in the recognition of a multilevel coordination problem among the basins of the watershed. The storm-drainage planning model was defined at the watershed level, and the optimization was achieved by a multilevel feasible decomposition scheme, where the land-use based hydrologic simulation model LANDSTORM was used locally, and separately for every local basin. A constrained cost-minimization scheme was adopted for the solution procedure. The resulting coordinating algorithm was proven to converge to the minimum cost solution and under some minor conditions of regularity of the modeling equations.

This methodology can be used to plan for changes to existing storm drainage systems, or in planning to accommodate projected urban growth as simulated by the LANDUSE model. In fact, for several such projections associated with a given watershed, the model URBDRAIN can associate a unique storm-drainage system cost with each land-use projection.

A.4 PUBLICATIONS

PWRRC Tech. Rept. 100, "Urban Growth in Water Resources Planning," by S. A. Dendrou, J. W. Delleur and J. J. Talavage, April 1978.

PWRRC Tech. Rept. 101, "Urban Storm-Drainage Systems Planning," by S. A. Dendrou, J. J. Talavage and J. W. Delleur.

S. A. Dendrou, J. W. Delleur and J. J. Talavage, "Systematic Planning of Urban Storm-Drainage Utilities," Proceedings Intl. Symp. on Urban Storm Water Management, Univ. of Kentucky, July 1978, pp. 229-234.

S. A. Dendrou, J. W. Delleur, "Reliability Concepts in Planning Storm-Drainage Systems," Proceedings Intl. Symp. on Risk and Reliability in Water Resources, Univ. of Waterloo, Ontario, Canada, June 1978, Vol. 1, pp. 390-410.

S. A. Dendrou, J. W. Delleur and J. J. Talavage, "Planning Storm-Drainage Systems for Urban Growth," Jour. of the Water Resources Planning and Management Division, Am. Soc. Civil Engrs., Nov. 1978.

S. A. Dendrou, J. J. Talavage and J. W. Delleur, "Optimal Planning for Urban Storm Drainage Systems," Jour. of the Water Resources Planning and Management Division, Am. Soc. Civil Engrs., Nov. 1978.

APPENDIX II

A COMPARATIVE APPLICATION OF SEVERAL METHODS FOR THE DESIGN OF STORM SEWERS

Four methods which may be employed in the design and analysis of urban drainage systems are investigated: the rational method, the Illinois Urban Drainage Area Simulator (ILLUDAS), the Instantaneous Unit Hydrograph of Sarma, Delleur and Rao, (SDR), and the Soil Conservation Curve Number Method (CN).

The above methods are applied to two subdivisions: Fair Oaks Estates located in Carol Stream, Illinois, and Barbarry Heights in West Lafayette, Indiana. Each method was used under varying conditions for the two subdivisions and the results are compared and analyzed. The storm of July 4, 1979, which caused severe flooding in Barbarry Heights, was input to ILLUDAS and the predicted areas flooding were compared to those areas which actually flooded.

The rational method required too much engineering judgment and too many hand calculations to allow the investigation of differing conditions or designs. The CN and SDR methods were found to give acceptable results for runoff volume, but the SDR method predicted peak runoff rates which were substantially lower than those computed by either ILLUDAS and the rational method.

PUBLICATION

For further details on this comparative study, the reader is referred to the following report:

PWRRC Tech. Rept. No. 118, "A Comparative Application of Several Methods for the Design of Storm Sewers," by C. B. Burke and D. D. Gray, Sept. 1979.

Water Resources Research Center
Lilly Hall of Life Sciences
Purdue University
West Lafayette, Indiana 47907